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DEVELOPMENT OF SITE FACTOR FOR SURFACE SPECTRAL ACCELERATION CALCULATION AT THE ALLUVIAL SOILS

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ABSTRACT: Calculation of surface spectral acceleration (SA) is one of the important steps in seismic design. The SA value can be obtained from bedrock spectral acceleration and multiplied by the site factor. According to ASCE/SEI 07-16, for short-period spectral acceleration (0.2 sec / S_S) greater than 1g and long-period (1 sec / S_1) greater than 0.2g, Site-Specific Propagation Analysis (SSA) shall be used for site factor calculation. SSA can be performed using three different data, bedrock elevation, dynamic soil profile, and acceleration time histories. The site factor can be calculated by comparing the surface to bedrock spectral acceleration obtained from SSA. This paper describes the development of the site factor at the alluvial area (soft soil area) in Semarang city, Indonesia. The site factor was calculated at 23 boring positions. Microtremor tests were conducted in this area to predict the soil dynamic profile. Five different acceleration time histories having magnitude from 6.5 Mw to 6.8 Mw and epicenter distance less than 10 km were collected for SSA. The average F_{PGA} and F_a values developed at 23 boring positions using SSA in this area were almost equal compared to the same site factor developed using the 2019 Indonesian Seismic Code. However, the average F_v calculated using SSA is lower than the same site factor calculated based on 2019 Code.

Keywords: Acceleration Time Histories, Bedrock, Microtremor, Site Factor, Site-Specific Propagation Analysis

1. INTRODUCTION

The site factor is one of the important values used for the development of surface spectral acceleration. Three different site factors F_{PGA} (Peak Ground Acceleration), F_a (short period or 0.2 sec) and F_v (1 sec) are required for the seismic design of buildings. According to the Indonesian Seismic Code 2019 [1] these three site factors can be obtained using Risk-targeted Maximum Considered Earthquake MCE_G, MCE_R-S_S and MCE_R-S_1, respectively. The problem of F_a and F_v calculation occurred during the development of the new 2019 Indonesian Seismic Code. ASCE/SEI 7-16 [2] as one of the references used the Indonesian Seismic Code introduced a different method for developing F_a value for soft soil (SE) area having MCE_R-S_S greater than 1 g and for F_v value having MCE_R-S_1 greater than 0.2 g. Site-Specific Propagation Analysis (SSA) should be conducted for developing F_a and F_v at SE (soft soil) area. Not all Civil Engineers in Indonesia are familiar with this new method. An alternative approach for developing these two values were applied following the research conducted by [3].

Two different problems occurred during the development of Site-Specific Propagation Analysis at site class SE area. The first problem related with the investigation of bedrock elevation and the soil profile from bedrock elevation up to the surface. The second problem related with the acquisition of acceleration time histories of specific earthquake events data which can be used for Site-Specific Propagation Analysis. This paper describes one-dimension Site-Specific Propagation Analysis (1D-SSA) for developing site factor at the study area. The analysis was performed at 23 boring positions at the alluvial area. Fig.1 shows the study area and the related soil investigations performed at the study area. The 1D-SSA was performed using bedrock elevation observed from single and array microtremor investigations at the study area [4]-[7]. The study was performed at the northern part of Semarang, Indonesia. Based on the geological map information, the majority of soft soil area is located at the alluvial area at the northern part of the City. Fig.2 shows the geological map of the city.

According to the previous 2015–2020 research conducted at the study area the bedrock elevation was predicted at a minimum of 225 meters below the surface level. Fig.3 shows the predicted bedrock elevation contour map developed based on the single station microtremor investigation. A comparative investigation was also performed using array microtremor. The investigation was performed at 4 different locations. The purpose of the array microtremor investigation was to verify the bedrock elevation at the study area. Fig. 4 shows two different results of the bedrock elevation investigation at array A and B. As can be seen in these figures the bedrock elevation was predicted at a minimum 250 meter below the surface level. The shear wave velocity (Vs) values were used as a parameter for bedrock elevation measurement. Rock sample having at least 1500 m/sec was conducted as a parameter used for bedrock elevation. The predicted soft-rock elevation (Vs ≥750 m/sec) or SB soil class [1], [2] is predicted in between 100 to 250 m below the surface level.

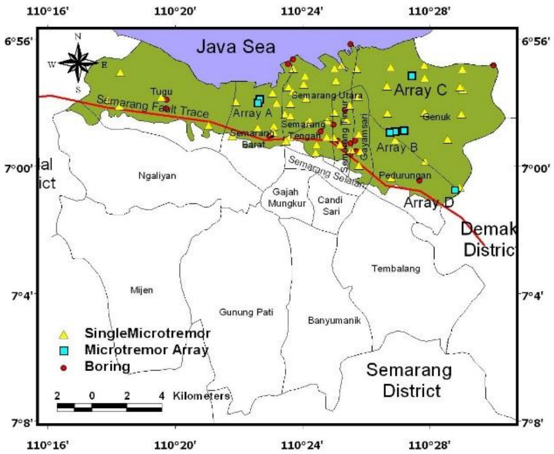

Fig.1 The study area and soil investigations (boring, single microtremor and array microtremor) performed at the study area

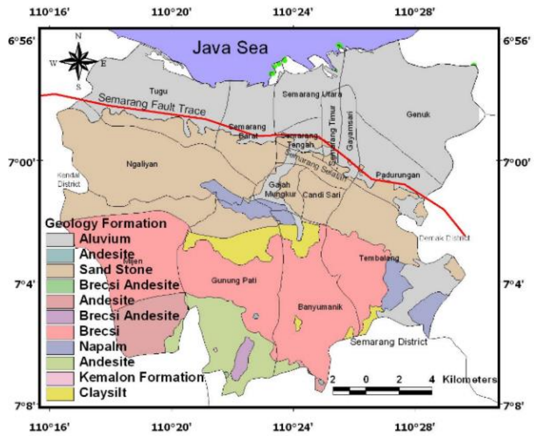

Fig.2 Geological map of the city

Due to the difficulties in development of soil profile, a 250 meters soil model was conducted for 1D-SSA. The distribution of soil dynamic parameters was calculated based on the empirical correlation of Vs (shear wave velocity) and N-SPT (Standard Penetration Test) and also between G (Shear Modulus) and N-SPT.

2. METHODOLOGY

The site factor F_{PGA}, F_a and F_v development at the study area were conducted following three basic steps, de-aggregation analysis, response spectral matching and 1D-SSA. The objective of de-aggregation analysis is to find the predicted magnitude (M) and distance (R) of earthquake scenario in terms of acceleration time histories that can be used for 1D-SSA.

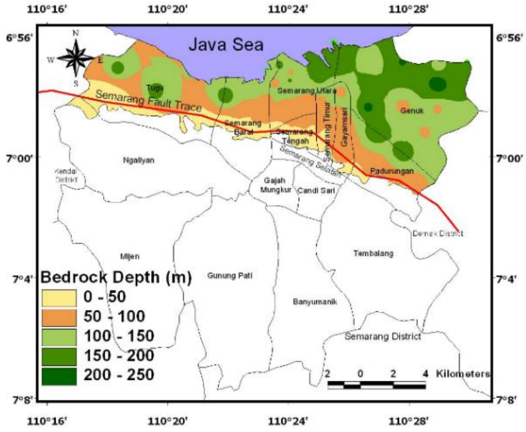

Fig.3 Predicted bedrock depth of the study area

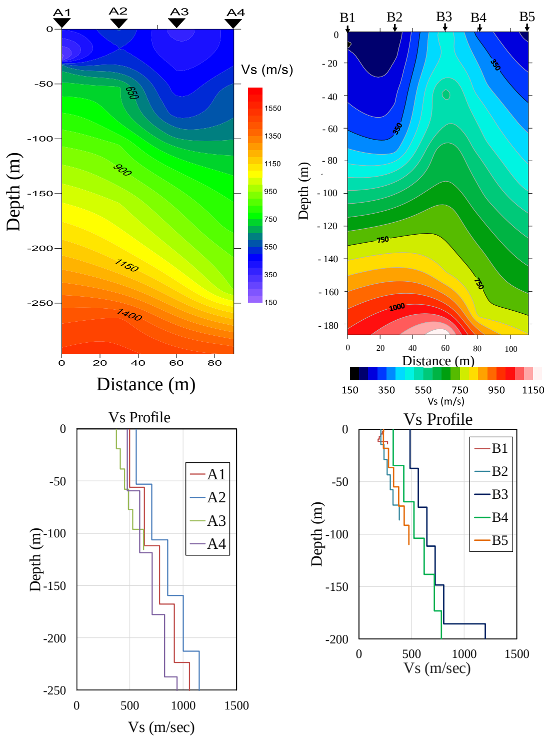

Fig.4 Predicted bedrock depth based on array microtremor investigation at array A and B

The second approach related with the matching analysis of time histories collected from earthquake event. The spectral acceleration MCE_G, MCE_R-S_S and MCE_R-S_1 were conducted as a target spectral acceleration used for spectral matching analysis. These three spectral accelerations were calculated based on Indonesian Seismic Code 2019. The final steps of site factor calculation related with the development of 1D-SSA. The site factor can be developed by comparing the surface to bedrock spectral acceleration obtained from 1D-SSA.

Fig. 5 shows de-aggregation analysis results of three different spectral acceleration (PGA, 0.2 sec and 1 sec) of shallow crustal fault seismic source model. The de-aggregation analysis was performed for the whole part of the city. According to these de-aggregation charts, the earthquake magnitude that can be used for the study area is in between 6.5 and 7 Mw. The correlation earthquake epicenter distance developed based on the de-aggregation analysis is in between 0-40 km. The alluvial area within the city is located at the north side of the Semarang fault trace [8]. The maximum distance of the study area to the seismic source is less than 10 km. According to these seismic earthquake scenarios, 5 (five) shallow crustal fault earthquake time histories were collected for site factor development. All earthquake data and time histories were collected based on reverse fault seismic model from Pacific Earthquake Engineering Research ground motion database. Table 1 shows the information of 5 earthquake events used in this study.

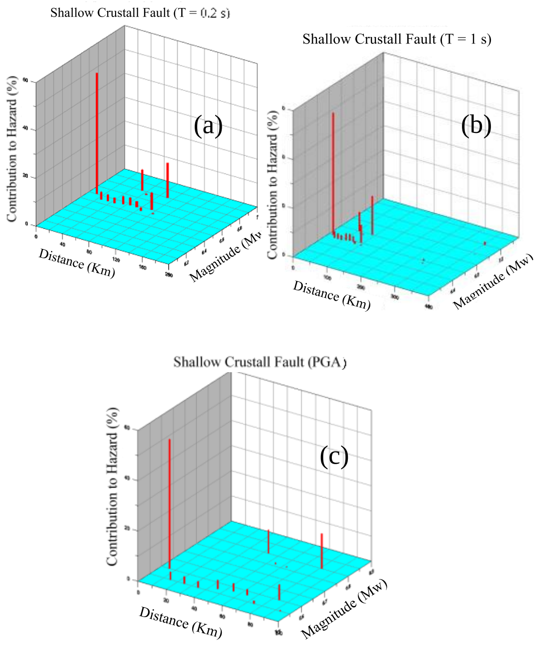

Fig.5 De-aggregation analysis results of shallow crustal fault source model for spectral 0.2 sec (a), spectral 1 sec (b) and PGA (c)

The response spectral matching analysis was conducted to 5 pair (North-South/NS and East-West/EW) direction ground motion data. Three Risk-targeted Maximum Considered Earthquake (MCE_G, MCER-S_S and MCER-S_1) used as a spectral acceleration target. Fig.6(a) shows matching spectral acceleration result conducted at boring no 15. Three spectral acceleration 0.3516 g, 0.8061 g and 0.3538 g displayed in this figure represent MCE_G, MCE_R-S_S and MCE_R-S_1 calculated at boring no 15 position. These three spectral accelerations were calculated based on Indonesian Seismic Code 2019. Fig.6(b) shows bedrock spectral acceleration at boring No 15 obtained from 1D-SSA. Fig.7 shows an example of two directions original acceleration time histories of Chuetsu-Oki earthquake data conducted at boring no 15. Fig. 8 shows the corresponding matched time histories developed from matching spectral acceleration analysis. The original and matched acceleration time histories developed for all 5 pair acceleration time histories were conducted at bedrock elevation.

Table 1 Earthquake event and related magnitude and epicenter distance used for site factor calculation

Earthquake Event	M (Mw)	R (km)
Chuetsu Oki (Japan, 2007)	6.8	5.0
Nahanni (Canada, 1985)	6.76	4.93
Niigata (Japan, 2004)	6.63	6.27
Northridge (USA, 2004)	6.69	5.26
San Simeon (California, 2003)	6.52	5.07

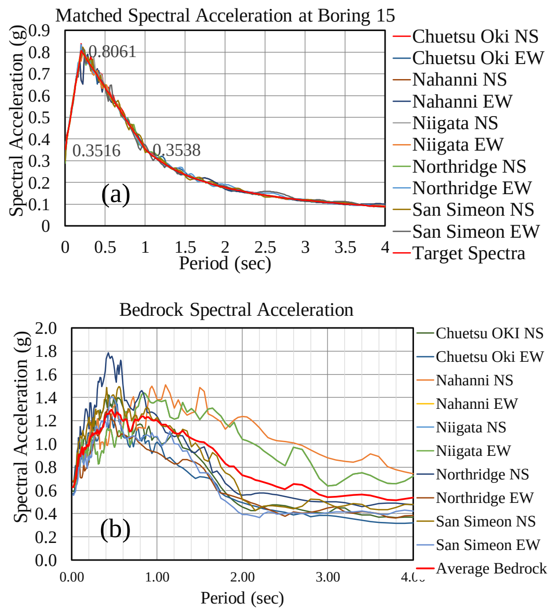

Fig.6 Matched spectral acceleration (a) and bedrock spectral acceleration from 1D-SSA (b) of 5 (North-South and East-West) acceleration time histories at boring no 15

The final analysis for site factor calculation was performed to obtain the surface spectral acceleration. One soil profile model having predicted bedrock elevation 250 meter was conducted for 1D-SSA. Four different Vs and N-SPT correlation models were elaborated for developing VS profile of each boring position. Table 2 shows 4 different Vs and N-SPT (shear wave velocity and N standard penetration) correlation. The “a” and “b” values displayed in this table represents correlation coefficients as displayed in Eq. 1. The N-SPT (N Standard Penetration Test) are N_{60} standard penetration value. Eq. 2 shows the empirical correlation of shear modulus of soil (G) and N-SPT. Three shear modulus and N-SPT correlations were applied for development of shear modulus values. Table 3 shows “c” and “d” values used for development of the soil shear modulus.

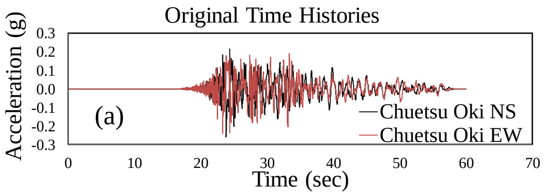

Fig.7 Chuetsu-Oki original time histories

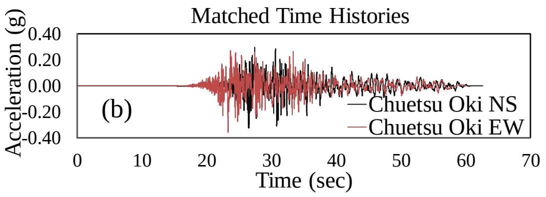

Fig.8 Chuetsu-Oki matched time histories at boring no 15

$$Vs = aN^b \quad (1)$$

$$G = cN^d \quad (2)$$

Table 2 Vs and NSPT correlation parameters

Correlation Model	a	b
Ohta & Goto (1978) [9]	82.1	0.35
Imai &Tonouchi (1982) [10]	93.7	0.31
Ohsaki & Iwasaki (1973) [11]	78.0	0.39
Partono et al. (2021) [12]	105.98	0.2643

Table 3 G and NSPT correlation parameters

Correlation Model	c	d
Ohsaki & Iwasaki (1973) [11]	11500	0.8
Imai &Tonouchi (1982) [10]	14070	0.68
Seed et al. (1983) [13]	6220	1.0

The 1D-SSA conducted at the study area was performed at 23 soil boring positions. The 1D-SSA was performed to obtain the F_{PGA}, F_a and F_v site factor. Fig. 9 shows three example soil parameters at boring no 15. Fig 10 shows the soil profile developed at the study area used for 1D-SSA.

The MCE_G, MCE_R-S_S and MCE_R-S_1 calculated at 23 boring positions shown at Fig. 11. The MCE_G and MCE_R-S1 calculated at 23 boring positions are almost equal, and distributed in between 0.30-0.40 g. The MCE_R-S_S calculated at 23 boring positions are almost constant and distributed form 0.7 up to 0.89 g. Based on ASCE/SEI 7-16, for MCE_R-S_S greater than 1 g and the building located at soft soil area (average N_{30} less than 15), the site factor F_a for spectral acceleration 0.2 sec shall be calculated using site analysis. Even-though the MCE_R-S_S at 23 boring positions less than 1 g, the comparative study for site factor calculation was conducted at the study area.

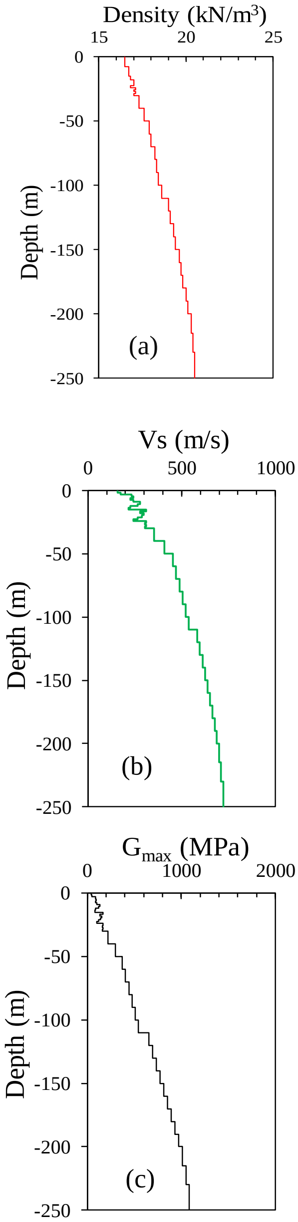

Fig.9 Soil parameters used for 1D-SSA at boring no 15, soil density (a), shear wave velocity (b) and soil

shear modulus (c)

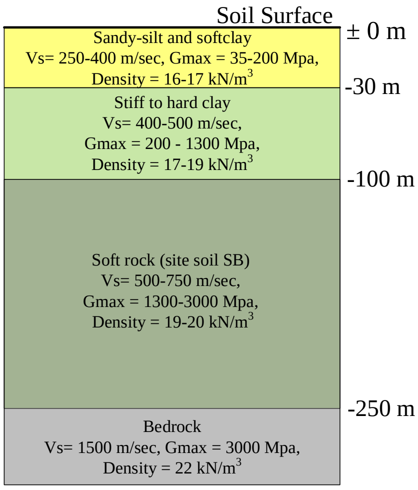

Fig.10 Soil profile and soil parameters used for 1D-SSA.

The predicted bedrock elevation at this boring position is 250 m. The thickness of each boring investigation for all 23 boring positions are not equal. The minimum depth of boring investigation is 30 m. However, the maximum depth of soil boring investigation is 60 m. Most of the soil boring investigations performed at the study area were conducted following the requirement for foundation design. The F_{PGA}, F_a and F_v site factors were calculated by comparing the surface to bedrock peak ground acceleration and spectral acceleration at 0.2 sec and 1 sec periods. The surface spectral acceleration was developed from two surface acceleration time histories. Fig.12 shows two surface acceleration time histories obtained from 1D-SSA at boring position No 15. Fig.13 shows an example of surface spectral acceleration obtained from 1D-SSA at boring position no 15. Based on this sample 1D-SSA analysis result, the average F_{PGA}, F_a and F_v site factor calculated from five scenario earthquake are 1.4646, 1.1592 and 2.8369, respectively. The analysis was conducted using NS and EW acceleration time histories.

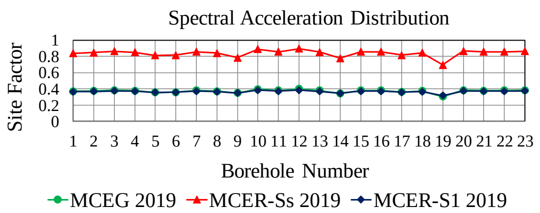

Fig.11 MCE_G, MCE_R-S_S and MCE_R-S_1 calculated at 23 borehole position

3. RESULTS AND DISCUSSION

The site factors developed using 1D-SSA analysis and conducted at 23 boring positions were evaluated and compared to the same site factor obtained from Indonesian Seismic Code 2019. Fig. 14 shows the three site factors F_{PGA}, F_a and F_v developed based on Indonesian Seismic Code 2019. According to this figure the site factor developed at the study area are almost constant. The F_{PGA} site factor are distributed in between 1.39 and 1.59. The F_a site factor obtained at 23 boring positions are also constant and the value are distributed in between 1.17 and 1.38. However, the F_v site factor calculated at 23 soil boring positions are distributed in between 2.45 and 2.73. The average values of F_{PGA}, F_a and F_v calculated using Indonesian Seismic Code 2019 are 1.46, 1.23 and 2.54 respectively.

Fig. 15 shows the three site factors distribution developed using 1D-SSA. All site factors developed using 1D-SSA are not constant and the values are varied between 0.6 and 3. The site factor F_{PGA} are distributed between 0.97 and 2.74. The site factor F_a are distributed from 0.68 and 1.85. And the F_v site factor are distributed in between 1.97 and 2.32. In average the F_{PGA} and F_v site factor developed using 1D-SSA is greater than the F_a site factor. In average the F_{PGA}, F_a and F_v calculated at the study area are 1.62, 1.23 and 1.48, respectively. Table 3 shows average site factor calculated using 1D-SSA developed from 5 different earthquake scenarios.

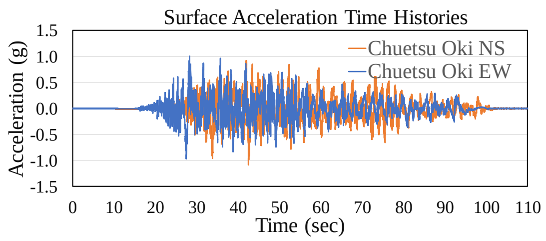

Fig.12 Surface acceleration time histories obtained from 1D-SSA at boring position no 15

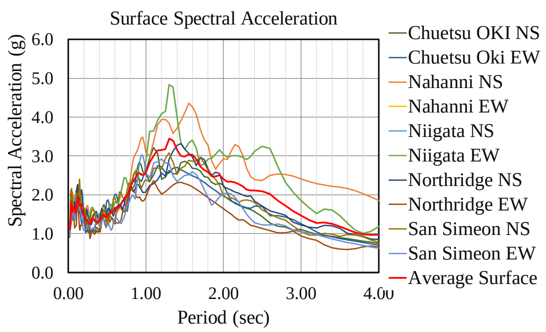

Fig.13 Surface spectral acceleration developed from 1D-SSA at boring position no 15

Compared to the site factor developed using

Indonesian Seismic Code 2019, in average the site factor F_{PGA} and F_a developed using 1D-SSA and the Indonesian Seismic Code 2019 are almost equal. However, the F_v site factor developed using 1D-SSA are smaller compared to the same site factor calculated based on Indonesian Seismic Code 2019. Fig. 16 shows the differences of three site factors developed using 1D-SSA and Indonesian Seismic Code 2019.

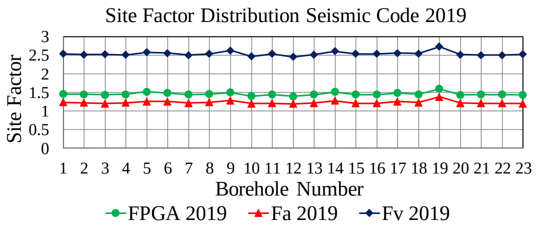

Fig.14 F_{PGA}, F_a and F_v distribution developed at 23 boring positions calculated using Indonesian Seismic Code 2019

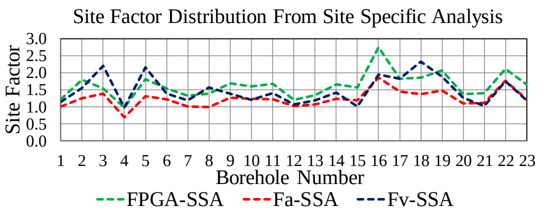

Fig.15 F_{PGA}, F_a and F_v distribution developed at 23 boring positions calculated using 1D-SSA

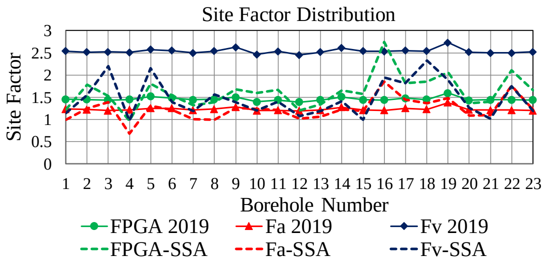

Fig.16 F_{PGA}, F_a and F_v distribution developed at 23 boring positions calculated using 1D-SSA and Indonesian Seismic Code 2019

Table 3 Average F_{PGA}, F_a and F_v site factor calculated using 1D-SSA of 5 earthquake scenarios

S F	Ch	Na	Ni	No	Sa
F_{PGA}	1.93	1.95	1.44	1.37	1.38
F_a	1.16	1.75	1.01	1.15	1.09
F_v	1.55	1.76	1.11	1.40	1.57

Note: Ch: Chuetsu Oki; Na: Nahanni; Ni: Niigata; No: Northridge and Sa: San Simeon Earthquake. SF: Site Factor. F_{PGA}: Peak Ground Acceleration. F_a and F_v: Site factor for spectral acceleration 0.2 sec and 1 sec respectively

According to these two calculation methods in developing site factor F_{PGA}, F_a and F_v, the site factor developed using 1D-SSA at alluvial or soft soil area as already suggested by ASCE/SEI 7-16 should be taken into account. Even-though the Ss values calculated at 23 boring positions at the study area are less than 1 g. The F_v values are smaller compared to the same site factor calculated using Indonesian Seismic Code 2019.

4. CONCLUSIONS

Site factor calculation at the alluvial area was conducted at 23 different boring positions. According to the Indonesian Seismic Code 2019, the average N_{30} at these 23 boring positions are less than 15. The alluvial area is located at soft soil area.

The three site factors F_{PGA}, F_a and F_v calculated and analyses based on Indonesian Seismic Code 2019 are not equal compared to the same site factor developed using 1D-SSA. The F_{PGA} and F_a calculated based on these two approaches are almost equal. However, the F_v site factor calculated using 1D-SSA are smaller compared to the same value calculated based on Indonesian Seismic Code 2019.

The site factor F_a and F_v for building upper structures calculation at the alluvial or soft soil area shall be evaluated due to the difference results calculation. Two different approaches shall be performed to get the real F_a and F_v site factor at alluvial area.

5. ACKNOWLEDGMENTS

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