



A Comparative Study of One-Dimensional Site Response Analysis on Deep Soft Clay Deposit using DEEPSOIL and NERA

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ABSTRACT Numerous high-rise buildings have been built in major cities in Indonesia. In high seismicity areas, such as Surabaya, the seismic behavior of structures is notably affected by the seismic characteristics of the subsurface soils. Typically, site-specific response analysis (SSRA) is conducted to determine the peak ground acceleration experienced at the ground surface. This paper compares one-dimensional site response analysis on deep soft clay deposits in Surabaya city using two commonly used 1D site response programs: DEEPSOIL and NERA (Non-linear Earthquake Site Response Analyse). A soil column model with 24 m thick very soft clay was developed. To represent different ground motion intensity, three levels of input motion were applied at the bedrock with peak ground accelerations (PGA) of 0.07g, 0.3g, and 0.51g. These input motions were then applied in a one-dimensional non-linear site response analysis to evaluate the seismic soil response at the surface. The evaluation involves examining the peak ground acceleration (PGA) and maximum shear strain profiles obtained from both software programs. The results indicate that the non-linear analysis conducted with NERA yielded greater amplification factors across all periods compared to the results obtained from DEEPSOIL. For the low-intensity motion, both software showed amplification of the input motion for all periods. In contrast, the spectral response obtained with DEEPSOIL demonstrated de-amplification trends for periods less than 1 s for the case of medium and high-intensity motions, whereas no de-amplification was observed from the results of NERA. This difference results in the amplification for medium and high-intensity motions can be attributed to the strength correction factors that are implemented in the DEEPSOIL software to take into account the representative shear strength of the soil layers.

KEYWORDS One-dimensional site response analysis, DEEPSOIL, NERA, soft clay

1 INTRODUCTION

The influence of soil conditions during an earthquake event is usually reviewed using one-dimensional (1D) site response analysis procedures to estimate the wave propagation at soil surfaces. A one-dimensional method has been a more prevalent approach as a consideration of the theory of seismic inclination when traveling upwards through horizontal layers tends to refract closer to a vertical direction (Kramer, 1996). The two common software programs that have been widely used in engineering practices are NERA (Bardet & Tobita, 2001) and DEEPSOIL (Hashash et al., 2020).

This paper uses the two software to analyze the site response of soft soil deposits in Surabaya, Indonesia, where the high-risk vulnerability of seismic excitation exists in this location with two active faults crossing the city as shown in Figure 1. Surabaya has a deep soft soil layer, thus requiring evaluation related to the soil amplification factor at the surfaces. Referring to SNI 1726 2019 (Indonesian Standard Code, 2019), site amplification factor is divided into several groups based on soil classification in which the values for period spectra tend to increase as the soil becomes softer. Previous study of site response in Jakarta, Indonesia has been conducted by several researchers (Delfebriyadi et al., (2019), Misliniyati et al., (2019), and Sengara & Komerdevi, (2020)) using 1D site response analysis with NERA, DEEPSOIL, and also STRATA (Kottke & Rathje, 2009). There was a previous study on site response of Surabaya by Irsyam et al., (2009), but the 2002 Seismic

design code which had lower level of earthquakes was used. Therefore, there is a need to reinvestigate Surabaya's site response, particularly considering its deep soft soil layers and the potential for seismic vulnerability due to the presence of two active faults intersecting the city.

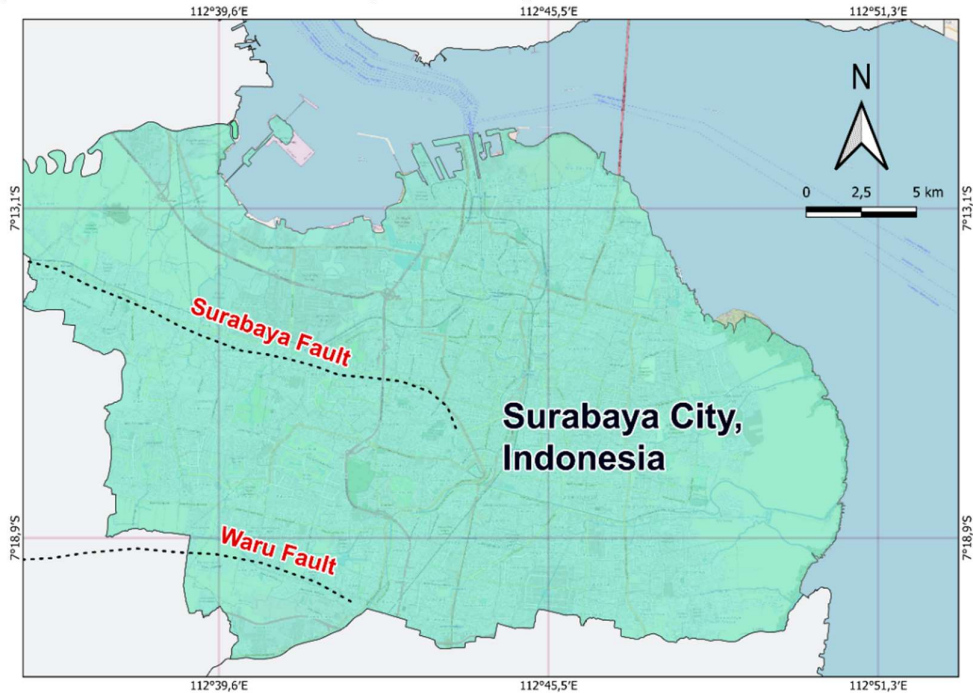


Figure 1 The map of Surabaya City, Indonesia with two active fault regions.

Recent study from Delfebriyadi et al. (2019) using a nonlinear site response analysis model performed by NERA showed that for soft soil site, there was amplification at the surface with a factor larger than 1.0. The amplification factor reduced with the level of intensity motion. The results were in alignment to the amplification factor available in Indonesian seismic code (Indonesian Standard Code, 2012). Different from Delfebriyadi et al. (2019), non-linear site response study conducted by Misliniyati et al., (2019) using DEEPSOIL software shows different trend. They performed parametric studies by varying the soil constitutive models, layer thickness, depth of bedrock, shear wave velocity of bedrock, and soil dynamic properties curve models. Their results showed that for soft soil site, there were de-amplifications in short to medium periods of spectrum. The differences in the soil amplification factors especially for soft soil site class among those literatures will be further investigated in this paper.

2 METHODOLOGY

2.1 Soil Profile Modelling

Figure 2 shows a standard penetration test (SPT) conducted in Surabaya city. As shown in the figure, there is a 24 m thick of soft clay deposit. From the SPT results, the soil profile can be divided into three different layers, i.e., soft, stiff, and very stiff. The parameters of each soil layer are shown in Table 1.

The soil investigation conducted did not reach the bedrock layer. From previous study, using the Horizontal to Vertical Spectral Ratio (HVSr), the bedrock in Surabaya ($V_s \approx 750$ m/s) is located around 150 m from the soil surface (Riyantiyo et al., 2017). The soil shear wave velocity and shear strength from 36 m depth to 150 m depth is linearly interpolated as suggested by Boore, (2004). The bedrock is assumed to have shear strength of approximately 1500 kPa. The interpolation is shown in Figure 3.

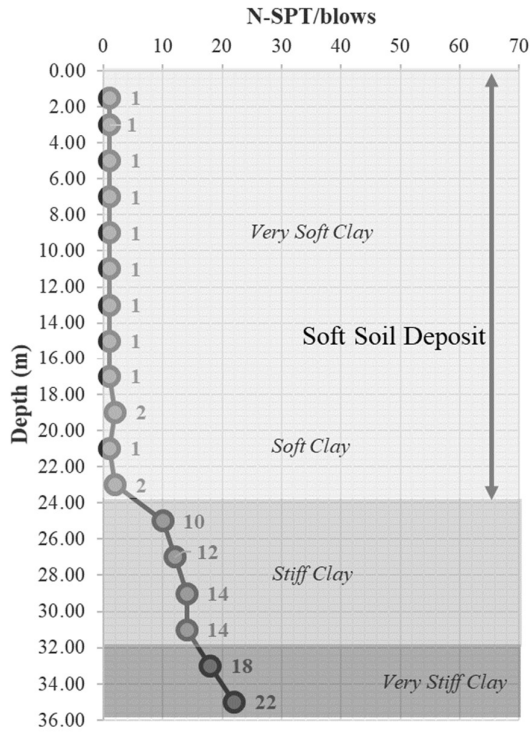


Figure 2 The bore-log NSPT with 24m depth of soft clay deposit in Surabaya.

Table 1 The description of soil modeling properties

Layer	Depth		Thickness (H)	Description	Average NSPT	S-wave velocity	Unit Weight
	m	m					
1	0	24	24	Soft Clay	1	101.46	17.00
2	24	32	8	Stiff Clay	13	220.46	17.00
3	32	36	4	Very Stiff Clay	20	257.28	17.00

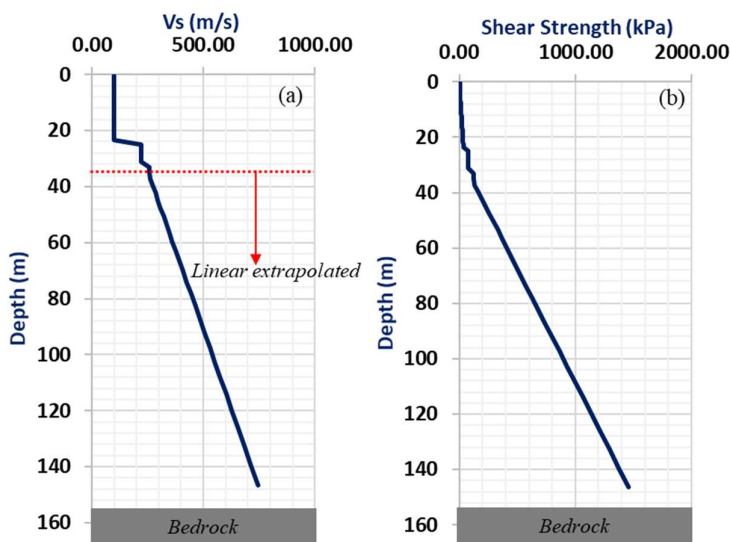


Figure 3 The soil column model up to bedrock level with linear extrapolation method (a) Shear wave velocity (b) Shear strength.

To ensure that the input motion can propagate properly through the soil model, the maximum thickness of each soil layer cannot exceed a certain value. For maximum frequencies (f_{max}) of 30 Hz (Hashash et al., 2020), the maximum soil layer thickness (H_{max}) can be determined using the following equation:

$$f_{max} = \frac{V_s}{4H_{max}} \quad (1)$$

Which, V_s is the shear wave velocity that can be determined from the correlation between NSPT and vertical overburden stress proposed by Wair et al. (2012) as shown in Table 2 below.

Table 2 Shear wave velocity correlation to NSPT and effective overburden stress

Soil Type	Shear Wave Velocity (m/s)
All soils	$30 N_{60}^{0.215} \sigma'_v{}^{0.275}$
Clays & Silts	$26 N_{60}^{0.17} \sigma'_v{}^{0.32}$
Sands	$30 N_{60}^{0.23} \sigma'_v{}^{0.23}$

2.2 Input Ground Motion at Bedrock

As the acceleration time history record in Surabaya City is not available, the procedure of modified ground motion at bedrock was implemented in accordance to SNI 8899 2020 (Indonesian Standard Code, 2020). The procedure of modification starts by defining the target spectrum at bedrock based on the Indonesian seismic code. Then, the representative earthquake mechanism, magnitude and distance for Surabaya were obtained from the Indonesia De-aggregation Map (PuSGeN, 2022). The target response spectrum was then defined using the Risk-Targeted Maximum Credible Earthquake (MCER) by multiplying the design response spectrum by 1.5 (Indonesian Standard Code, 2019) as shown in Figure 4.

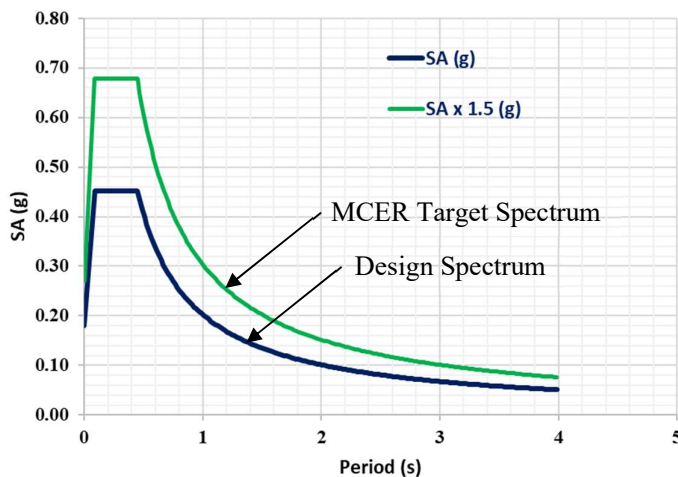


Figure 4 Target Spectrum at Bedrock.

This procedure aims to find the historical ground motion records of seismic events with similar source-site distances and magnitudes that have corresponded with the 2500-year earthquake return period. According to de-aggregation map of Indonesia, three different mechanisms are considered. However, in this study only shallow crustal earthquake was considered due to the shorter earthquake duration for efficient computational effort. The representative magnitude and source-distance of this earthquake is shown in Table 3.

Table 3 De-aggregation Result of Surabaya City for Shallow Crustal Mechanism

Period	Source	Mw _{Avg}	R _{Avg}
PGA	Shallow Crustal	6.1	35

The final stage of modified ground motion is the matching procedure using tight spectral matching in order to fit the spectrum of the original time history record to the target spectrum according to Figure 4. The acceleration, velocity, and displacement time histories of matched ground motion is shown in Figure 5. To ensure there is no significant change in the original motion's characteristic, the matching result was controlled by comparing the normalized arias intensity between the original and modified motions as shown in Figure 6.

The result of modified ground motion produces a similar peak ground acceleration (PGA) at bedrock with $PGA = 0.31 \text{ g}$ (see figure 5) according to the target spectrum from SNI 1726 2019 in Surabaya City. This motion is defined in this study as medium intensity motion. In order to evaluate the influences of input ground motion with different intensities for one-dimensional site response analysis, two original time histories with PGA of 0.07g and 0.51g were added with similar characteristic of seismic mechanisms to represent low-intensity and high-intensity motions. However, the spectral matching procedure was not conducted for these additional motions. The three different acceleration time histories that were used in this study are shown in Figure 7 consisting of low-intensity motion, medium-intensity motion, and high-intensity motion with PGA from 0.07 g , 0.31g , and 0.51g respectively.

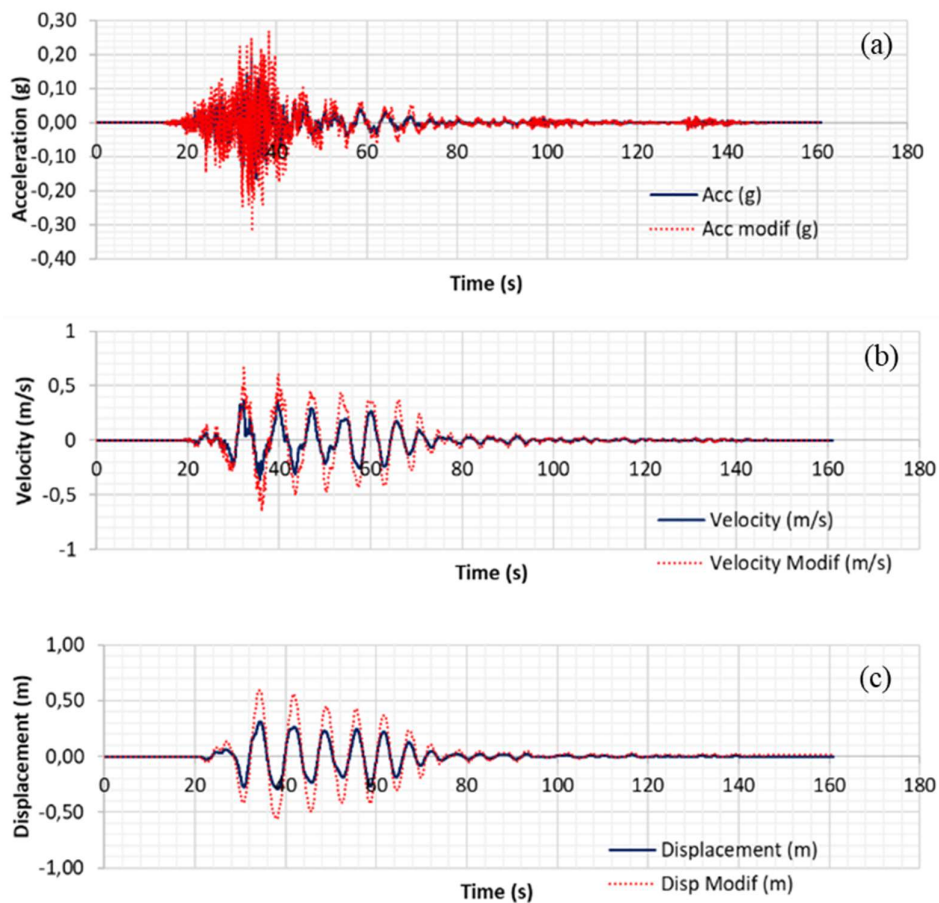


Figure 5 The comparison between original and modified ground motion at bedrock (a) acceleration (b) velocity (c) displacement.

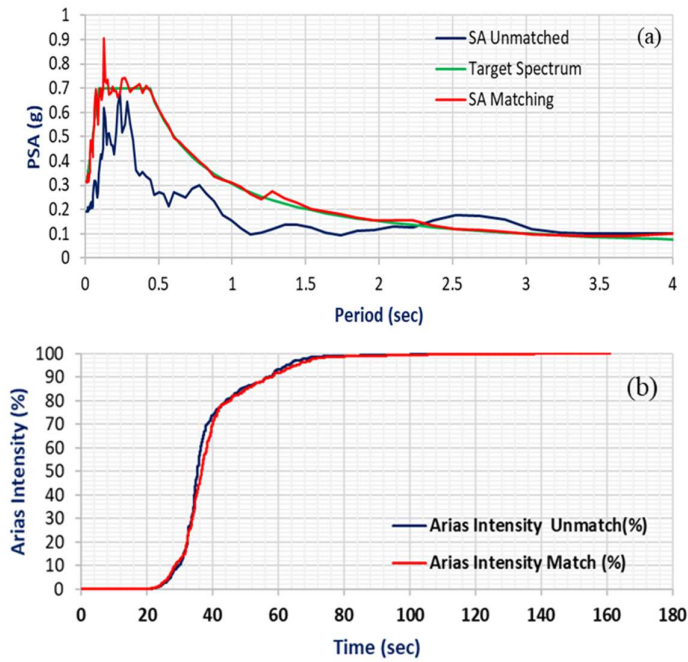


Figure 6 (a) Spectral matching and (b) normalized arias intensity of modified ground motion at bedrock.

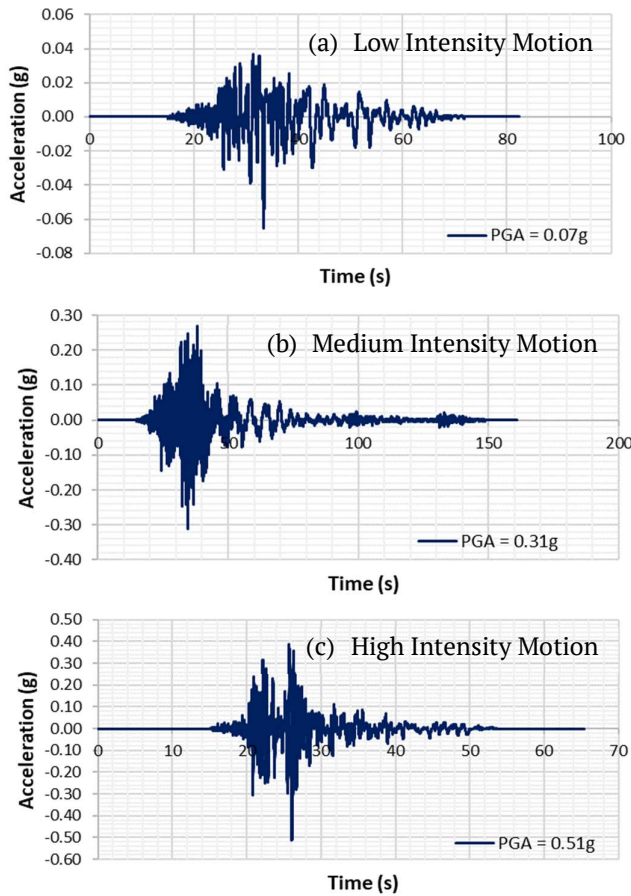


Figure 7 Input motion at bedrock with a variation of PGA's intensity.

2.3 DEEPSOIL Model Approach

DEEPSOIL software was developed by Hashash et al. (2020) and it has many functions to analyze one-dimensional site response analysis such as types of analytical methods (linear, equivalent-linear, or non-linear), soil constitutive models, modulus reduction and damping curves. The nonlinearity of soils resulting from medium to large ground movements is influenced by the changes in stiffness and the dissipation of energy (Hashash & Park, 2001). In order to model ground response analysis, the soil dynamic parameters are required in terms of shear modulus reduction and damping ratio. The formulation of shear modulus reduction and damping curve has been presented by many researchers during the past 50 years such as Seed & Idriss (1970), Vucetic & Dobry (1991), and Darendeli, (2001) in which those models have been available in the latest version of DEEPSOIL program. In general, the modulus reduction and damping ratio formula depend on soil types, plasticity index (PI), overconsolidation ratio, and confining pressure based on experimental results.

Parihar & Panjamani (2015) studied the selection of modulus and damping curves. Their results showed that for sandy soils, the upper limit curve model proposed by Seed & Idriss (1970) gave more accurate result. As for clayey soils, Vucetic & Dobry (1991) model with $PI = 10$ produced most appropriate results. Even though the family of curves by Vucetic & Dobry (1991) consider the influences of PI, however according to Guerreiro et al. (2012), there is no PI data that is above 60%. In addition, the data is also restricted to a rather limited strain range. In addition, the study of Guerreiro et al. (2012) also showed that the family curves obtained from Darendeli, (2001) appear to be capable of encompassing all significant influences throughout the entire strain ranges. However, for large strain levels, the soil shear strength tends to be underestimated or overestimated. There was limitation that the laboratory experiments were not able to capture the reduction in damping ratio curves at extremely large strain levels. To address this issue, it is important to apply a shear strength correction in order to more accurately represent the shear strength at large strains, as recommended by Phillips & Hashash (2009). Thus, a simplified non-linear constitutive model was proposed by Groholski et al. (2016) or better known as the General Quadratic/Hyperbolic (GQ/H) model. The GQ/H model has curve fitting procedures to automatically correct the shear strength determined from reference curves. Therefore in this study, Darendeli (2001) reference curves (Figure 8) along with GQ/H constitutive model by Groholski et al. (2016) were used in site response analysis.

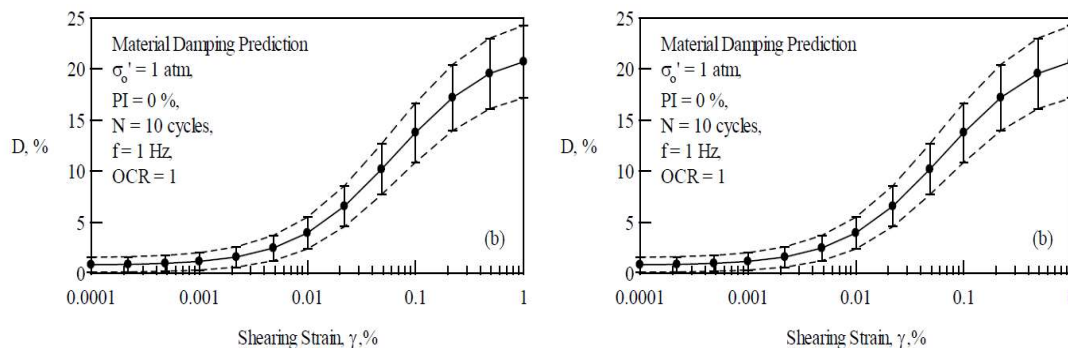


Figure 8 The shear modulus reduction and damping curve proposed by Darendeli (2001).

2.4 NERA Model Approach

On the other hand, NERA or Nonlinear Earthquake Response Analysis (Bardet & Tobita, 2001) implemented soil constitutive model based on Iwan (1967) and Mróz (1967) model to represent the hysteretic stress-strain behavior of soil. However, the IM (Iwan and Mróz) model does not have damping ratio at very small strain, as shown in Figure 9. The damping ratio also decreases in the range of 3-10% before increasing significantly for very large strains.

In terms of the dynamic curves, NERA provides the formulation of shear modulus reduction and damping curve according to Seed & Idriss (1970) for sandy soils and Sun et al. (1988) for cohesive

soils. Different to DEEPSOIL, there is no shear strength correction model implemented in NERA for large strain.

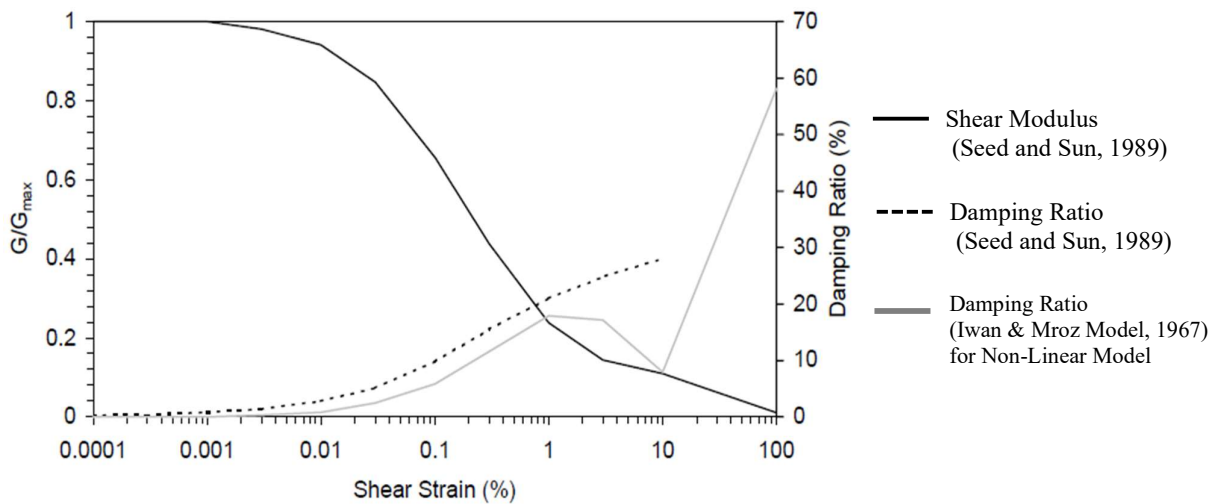


Figure 9 Example of damping ratio calculation based on the NERA Manual Report (Bardet & Tobita, 2001).

3 RESULTS AND DISCUSSION

Figure 10a shows the peak ground acceleration (PGA) and maximum shear strain for three different intensity motions. The PGA profile for the case of low-intensity motion obtained from DEEPSOIL tends to be stable during its propagation to the surface, while NERA shows a substantial increase in PGA when entering the soft soil layers around 25 m depth. However, for medium-intensity and high-intensity motion, the PGA obtained from DEEPSOIL decreases when passing the softer layers. The reason for this deamplification is due to the large shear strain level in this soft clay layer as shown in Figure 10b. This large shear strain levels generated large hysteretic damping that caused the reduction of seismic energy and hence reduction of PGA in this layer. Similar behavior was observed from NERA for high-intensity motion case. However, for medium intensity motion, the PGA profiles obtained from NERA tended to increase in the soft clay layers. This can be attributed to the strain level of 1.5% at 25 m depth in which the damping ratio used by NERA decreases when the strain level is higher than 1% (Figure 9).

Figure 11a shows the comparisons of the surface spectral acceleration between DEEPSOIL and NERA for three different intensity motions. For low intensity motion, NERA showed larger PSA from 0.03s to 0.5s period compared to DEEPSOIL. The difference was more significant for medium and large intensity motions. PSA obtained from NERA is about 0.6-1.2g, 2-3 times larger than PSA obtained from DEEPSOIL. These results indicate that the reduction of accelerations due to the large strain levels was not observed only at PGA, but also in the period above 1s for PSA.

In terms of amplification factors, which is defined as the ratio of the response spectrum at the surface and response at the bedrock, the comparison between DEEPSOIL and NERA is shown in Figure 11b. For low-intensity motion, both software showed amplification factor larger than 1 for all period range. However, for medium and high-intensity at short to intermediate periods ($T < 1$ second), the amplification factors obtained from DEEPSOIL was less than 1, while NERA was larger than 1 for medium intensity motion. For long periods ($T > 1$ second), both software showed amplifications with the amplification factors around 1.5-2.0. This implies that the energy of input motion was dissipated dominantly for high-frequency contents due to the high level of strains which generated the large hysteretic damping.

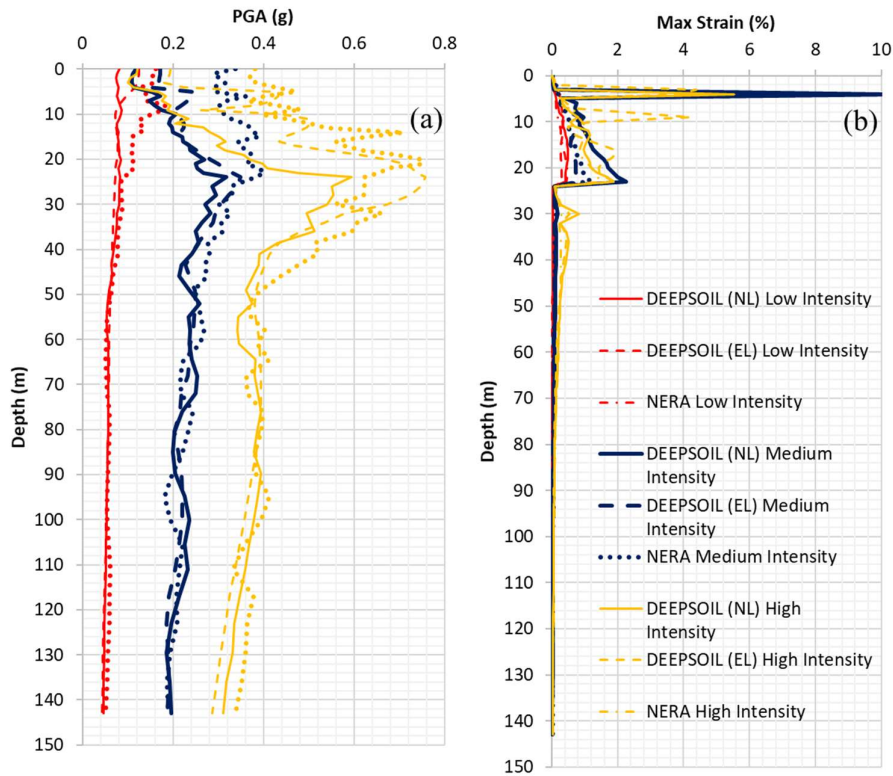


Figure 10 (a) PGA (Peak Ground Acceleration) (NL = Non-Linear; EL = Equivalent-Linear) and (b) Max Strain Profile Result.

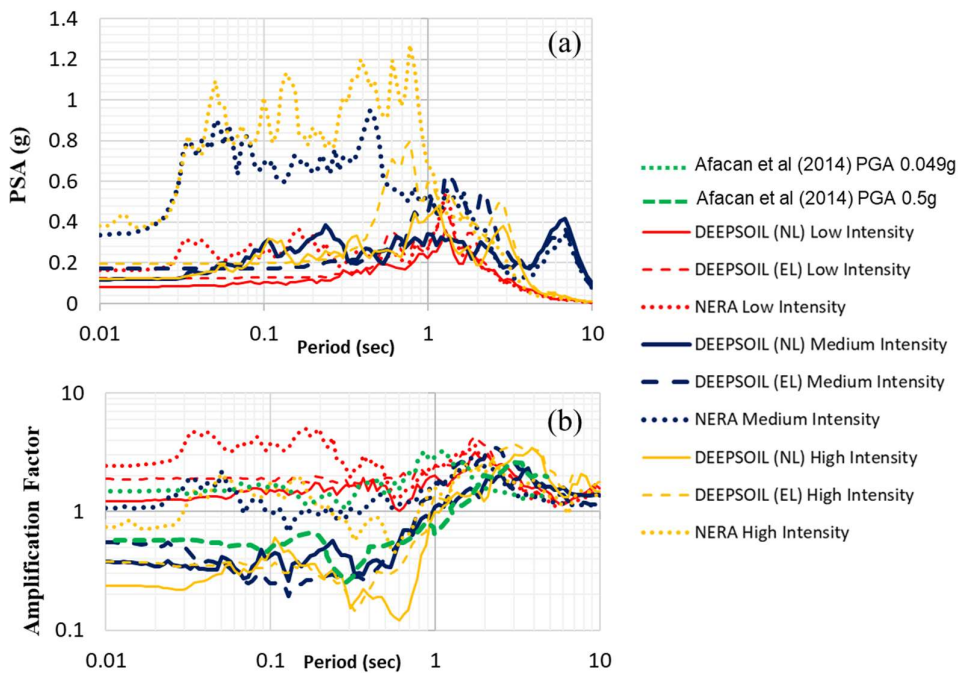


Figure 11 (a) Response Spectrum at Surface and (b) Amplification Factor

The deamplification results for high-intensity motion obtained from DEEPSOIL agreed with the centrifuge test results by Afacan et al. (2014) whereby deamplification was observed when wave

was propagating in the soft clay layers with similar intensity of motion of 0.50g. The soil profile used in Afacan et al. (2014) is shown in Figure 12. The upper 18 m has low shear strength of < 30 kPa, implying similar soft soil conditions as the current study.

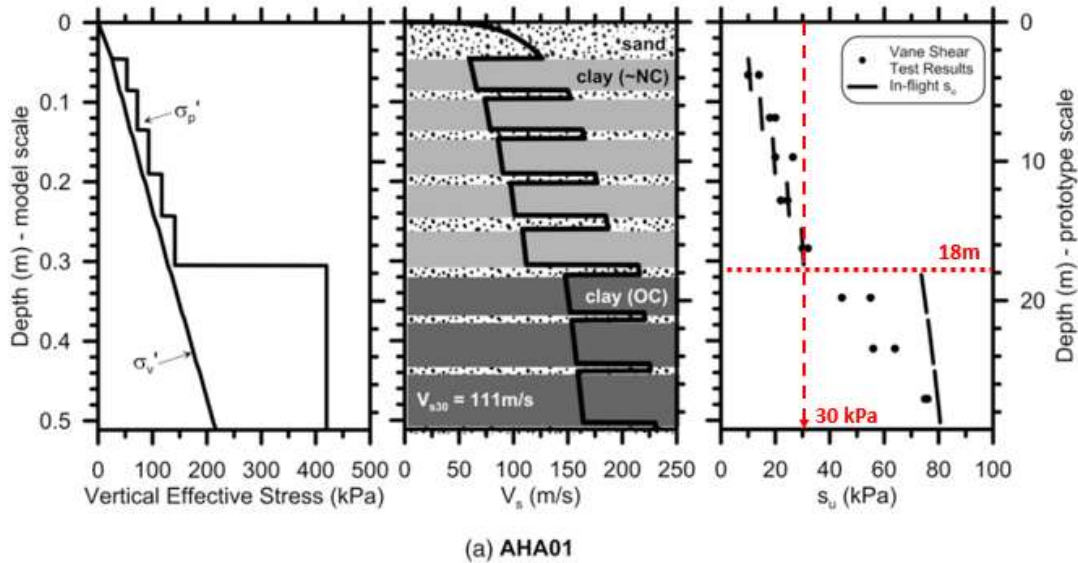


Figure 12 Soil parameters of centrifuge test by (Afacan et al. 2014)

The centrifuge test results showed that low-intensity motion ($PGA = 0.049g$) resulted in amplification factor of larger than 1 for all periods of spectrum. In contrast, high-intensity motion ($PGA = 0.5g$) resulted in amplification factor of lower than 1 for short to intermediate periods spectra as shown in the figure 13 below.

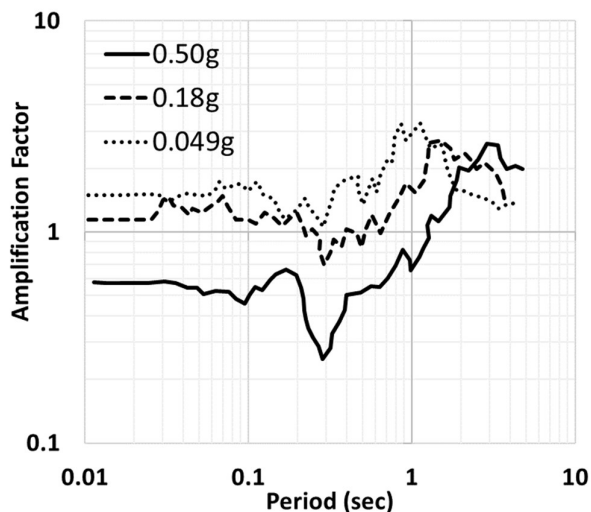


Figure 13 The amplification factor with different intensities from The Centrifuge Test Result (Afacan et al., 2014).

Those results from Afacan et al. (2014) indicate similar observation to the results of current study using DEEPSOIL program. This implies that the strength correction at large strain level was found to be important in the site response analysis to better capture the cyclic non-linear behavior of the soil subjected to large shaking. This strength correction feature is available in the DEEPSOIL software by using the GQ/H hysteretic model proposed by Groholski et al. (2016).

4 IMPLICATIONS

This study has a potential implication for practicing engineers. When comparing the amplification factors obtained from two different 1D site response software with Indonesian National Standard of SNI 1726 2019 (Indonesian Standard Code, 2019) for site class SE, the response spectrum obtained from NERA has a similar spectral acceleration with SNI code as shown in Figure 14. On the other hand, the results from DEEPSOIL had a lower spectral acceleration in the range of low to moderate periods which aligned with the centrifuge study of Afacan et al. (2014). This implies that the design of using SNI 1726 2019 tended to be conservative for soil profile (i.e., soft) and intensity motions considered in this study. This study also shows that performing site response analysis is recommended especially for soft soil deposit with low shear strength.

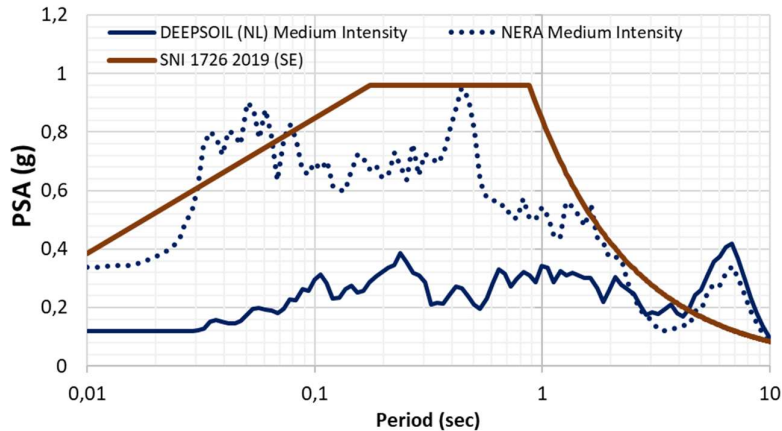


Figure 14 Response Spectrum at Surface compared to SNI 1726 2019 (SE).

5 CONCLUSIONS

This study compared the site response analysis from two commonly used software programs, i.e., DEEPSOIL and NERA. Three different intensity motions were used to evaluate the amplification factors for all spectrum periods. For low intensity motions, both software tended to have similar results. However, for medium and high intensity motions, DEEPSOIL showed deamplification (amplification factor < 1) due to large shear strain that occurred in the soft clay layers. On the other hand, NERA produced amplification (amplification factor > 1) for medium intensity motion for all periods.

To verify the results, a previous centrifuge experiment by Afacan et al. (2014) for high intensity motion was referred. It was found that DEEPSOIL tended to have similar results with Afacan et al. (2014), showing that strength correction control implemented in DEEPSOIL along with Darendeli dynamic curves were able to better capture the seismic soil response than NERA during large earthquake. This indicates that NERA analysis tended to be more conservative for soil profile and intensity motions considered in this study.

For design purpose, the findings from this study rises awareness that practicing engineers and government agency should consider site-specific evaluation when determining amplification factors at the ground surface. However, further study is recommended to better understand the seismic wave propagation behavior under wider range of intensity motions, shear strength profiles, and thickness of the soft clay deposit.

6 ACKNOWLEDGEMENT

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