A Comparison Between VS30 Based- and Natural Frequency Based- Site Amplification Factor for Three Different Types of Soil Classification

B.A. Yogatama[1] and B.A. Tirta[1]
[1]PT. Witteveen+Bos Indonesia, Jakarta, Indonesia
E-mail: bonifacius.yogatama@witteveenbos.com, budiwan.tirta@witteveenbos.com

ABSTRACT: In this paper, a comparison is shown between site factors derived from the conventional VS30 parameter based on SNI 1726-2012 and from the soil profile natural frequency (f0) referred to Cadet et al (2012). Three series of stochastic site response analyses (SRA) as a benchmark for the former two approaches have been performed considering linear viscoelastic condition from three large data sets. The data sets were stochastically generated to represent different site classification uniformly: soft, medium, and hard soil (SE, SD, and SC soil class, respectively). For each stochastic model set, 1000 soil profiles were generated and its linear responses were computed to derive the spectral ratio at 1 Hz (FV – SA 1 s), 5 Hz (FA – SA 0.2 s), and 25 Hz (PGA). Correlation scatter charts were then developed to observe and to check the performance of each approach. The charts showed correlation of site factors based on the VS30 and f0 parameters with the SRA modeling. Based on the correlation, the best site amplification factor estimation approach for each spectral acceleration (FPGA, FA, FV) and for each soil class (SE, SD, SC) is provided.
Keywords: site factor, site amplification, local site effect, natural frequency, VS30

1. INTRODUCTION

In a seismological point of view, earthquake wave propagation can be classified into three different phases: (1) earthquake rupture or source effect, (2) wave propagation through crustal rock medium, and (3) local site effect. All above three aspects may introduce either amplification or de-amplification over a certain frequency range. Although its depth scale is the smallest compared to the other two (easier to be characterized by an engineer), the local site effect contributes a large uncertainty to produce the recorded ground motion at surface. Local site effect has many forms, the most common is the wave amplification at soft sediment overlying a rigid bedrock, which is the main topic of this paper.

The consideration of local site effect in a modern seismic code has been implemented after the occurrence of Loma Prieta earthquake, California in 1989. Borcherdt (1994) collected many accelerometer recordings from different stations of the event in California region, studied the relation between site characteristics and the corresponding amplification, and proposed a correlation between V_{S30} (the average shear velocity of the top 30 m) and the amplification factor for PGA, short period and long period spectral acceleration (0.2 s and 1.0 s). Such correlation became popular since V_{S30} is a parameter which can be obtained with less effort. This study is then implemented in many seismic codes around the world, starting from NEHRP provision 1997 (implemented in UBC 1997) and eventually adopted in the latest Indonesian seismic code SNI 1726-2012.

Despite its high popularity, scientific community put a high doubt on the use of such simple parameter to characterize the amplification of a soil profile, which contains a lot of uncertainty along the whole depth. V_{S30} site factor fails to take into account the effect of soil layer deeper than 30 m, e.g. for region with a thick alluvial deposit (for example Jakarta). Castellaro et al (2008) criticized the way Borcherdt (1994) draw the regression line of such correlation, and showed that actually there is very little correlation between V_{S30} and site factor. Cadet et al (2012) used a lot of KiK-NET data from Japan to develop a relation between site amplification factor at a certain frequency with the natural frequency (f_0) of a soil profile. Their study suggested that f_0 is a better site proxy than V_{S30} as it has smaller misfit value at all frequency range. Zhao and Xu (2013) also studied the same thing but using a different set of KiK-NET data, and they stated that natural period (T) of a soil profile is a better proxy than V_{S30} for sites with high natural period (very soft sediment or very thick alluvial deposit).

In this paper, a performance comparison is made between the site factors derived from V_{S30} (herein denoted as SNI approach) with the site factors derived from the soil profile natural frequency (f_0) as developed by Cadet et al (2012) (herein denoted as SAPE: Site Amplification Prediction Equation).

The comparison is performed for different range of soil profile, covering from very soft sediment (low frequency, low V_{S30}) up to very hard rock / outcropping rock (high frequency, high V_{S30}). In order to do that, a numerical method is implemented to create thousands of stochastic artificial soil profile, which then the natural frequency and the V_{S30} of each profile will be calculated. Afterwards, a linear site response is performed for each soil profile to derive the computed site factor for three different spectral acceleration levels: F_{PGA}, F_A (0.2 s), and F_V (1.0 s). The annotation of these site factors is made similar to those parameters used in NEHRP provision and SNI 1726-2012.

The goal of this paper is to compare the computed site factors with the estimated site factors from the two methods (SAPE and SNI) and to provide an explanation of the possible discrepancies between them. The validity of this linear site response analysis is considered sufficient for this purpose, since SAPE was also developed only for linear elastic condition, and the output variability due to non-linear behavior as described by Yogatama and Lengkeek (2017) is not expected.

2. ANALYSIS PROCEDURE

2.1 Frequency-based site factor (SAPE approach)

In their publication, Cadet et al (2012) developed a different set of site factor of ground motion at a certain frequency based on the natural frequency of the soil profile from KiK-NET ground motion database. Thousands of weak motion surface and downhole accelerometer recordings from approximately 400 sites were used to derive the amplification factor (spectral ratio) for each site. Before the downhole recording was used as the reference motion to derive the spectral ratio, the signal was corrected against depth and normalized against impedance contrast in order to uniformly represent a signal recorded at a generic outcropping rock station with a shear wave velocity of 800 m/s. This procedure is necessary to be performed since KiK-NET downhole sensors are positioned at varying bedrock depth and velocity (different for each site) and such issue will create a bias if not treated properly.

After the spectral ratio has been derived, then all spectral ratios were normalized against the natural frequency of each site so that the spectrum peak is positioned at unity, with the x-axis as a dimensionless frequency. The dimensionless frequency itself is the ratio between the considered frequency of spectral ratio value and the natural frequency of the respective amplification spectrum. A regression analysis is then made to correlate the amplification factor (spectral ratio) and the site proxy (soil natural frequency) at different value of dimensionless frequency. The equation of their SAPE method is given by the following formula:

$$G_x(v) = \left(\frac{X_{ref}}{X}\right)^{\beta} \quad (1)$$

where G_x is the estimated site amplification factor, X is the soil natural frequency, X_{ref} and β are the coefficients derived from linear regression at a considered dimensionless frequency, v. The coefficient table of X_{ref} and β is given as an appendix in their publication.

2.2 V_{S30}-based site factor (SNI approach)

In this paper, the other site proxy for comparison is the 30 meters averaged shear wave velocity (VS30) which is determined by:

$$Vs_{30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{Vs_i}} \quad (2)$$

where di is the layer thickness up to 30 meters depth and VSi is the shear wave velocity of layer i (in m/s). The calculated VS30 then corresponds to five soil classifications (Table 1), each has its own site amplification factor which was determined based on Borcherdt (1994). The linear site amplification factors as applied in SNI 1726-2012 are represented in the following table.

Table 1 Site classification and its corresponding linear site amplification factor (SNI 1726-2012)

Soil Class	VS30 (m/s)	FPGA (PGA<0.1g)	FA (SS<0.25g)	FV (S1<0.1g)
SA	> 1500	0.8	0.8	0.8
SB	750 – 1500	1.0	1.0	1.0
SC	350 – 750	1.2	1.2	1.7
SD	175 – 350	1.6	1.6	2.4
SE	< 175	2.5	2.5	3.5

2.3 Stochastic analysis

The simulation framework of this study is to divide the stochastic model of soil profile into three different VS30 ranges:

- Model 1 (soil class SE) → Low range site frequency: approximately $f_0 \leq 1$ Hz
- Model 2 (soil class SD) → Medium range site frequency: approximately 1 Hz < f0 < 5 Hz
- Model 3 (soil class SC) → High range site frequency: approximately $f_0 > 5$ Hz

The purpose of this division is to have a clear verification on the reliability of FA (0.2 s – 5 Hz) and FV (1 s – 1 Hz) for sites with broadband f0 and VS30.

The artificial soil profiles are modeled by assuming three-layered profile overlying a halfspace (bedrock, soil class SB). The thickness and the velocity of each layer in each model set are determined stochastically using truncated Gaussian distribution with the parameter set as presented in Table 2.

Table 2 Statistical parameters for developing artificial soil profiles

		V_S (m/s)		thickness (m)	
		mean	**std**	**mean**	**std**
model 1; class SE	layer 1	100	10	10	2
	layer 2	120	30	10	4
	layer 3	150	30	10	5
model 2; class SD	layer 1	160	20	10	2
	layer 2	350	40	10	4
	layer 3	500	60	10	5
model 3; class SC	layer 1	550	20	10	2
	layer 2	650	40	10	4
	layer 3	700	50	10	5

Aside from layer thickness and shear velocity, unit masses and material damping are also required for linear viscoelastic analysis. In this study the unit masses and material damping of each layer is determined by using an approach proposed by Cadet et al (2012).

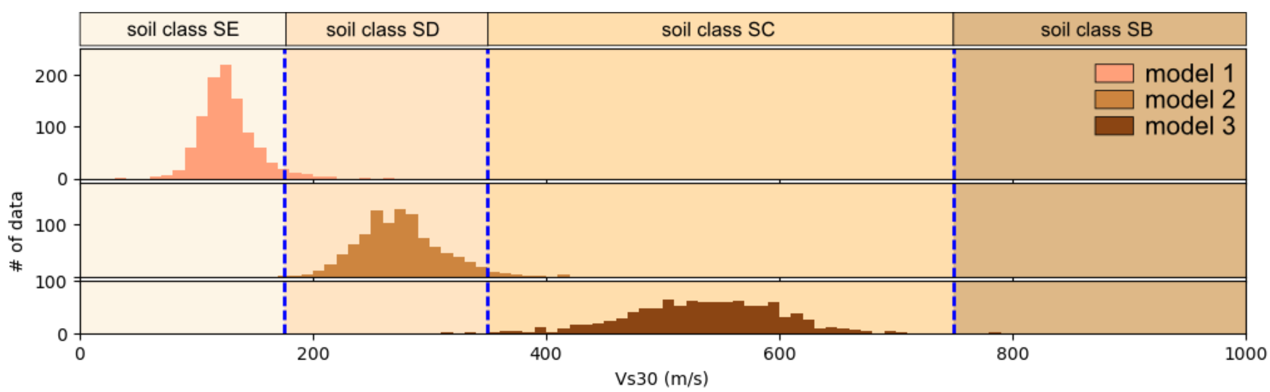
The unit masses of each layer are assumed to be increasing with shear wave velocity, as follow:

- ρ = 1.7 g/cm³ for VS < 180 m/s
- ρ = 2.0 g/cm³ for 180 < VS < 360 m/s
- ρ = 2.2 g/cm³ for 360 < VS < 1500 m/s
- ρ = 2.5 g/cm3 for VS > 1500 m/s

The damping ratio of each layer is represented as quality factor (Q) and is derived using the following formula, with V_S is the shear velocity in m/s.

$$Q = V_S/10$$

Based on the statistical parameter set and assumptions as described above, 1000 artificial soil profiles are created for each model set, and the histogram of the site frequency (f_0) and V_{S30} are presented in the figure below. V_{S30} is determined using Equation (2), while f_0 is determined from the transfer function of each profile.



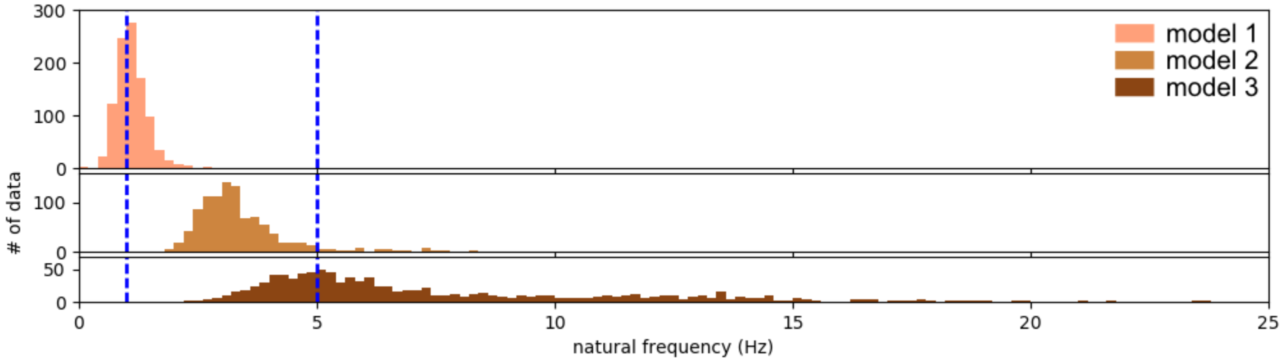


Figure 1 Histogram of natural frequency and V_{S30} for all model sets

The above histograms show that not all generated soil profiles comply within the desired frequency/VS30 range, for instance not all profiles of model 1 have f0 lower than 1 Hz, as there is still about 50% which has larger than 1 Hz. However, large portion of the profiles have VS30 value lower than 175 m/s which put them to soil class SE. Most of soil profiles in model 2 lie within the desired range, for both f0 and VS30. Similar to model 1, part of soil profiles in model 3 have f0 lower than 5 Hz while the rest has f0 exceeding beyond 5-10 Hz. However, most of the profiles have VS30 between 350-750 m/s (soil class SC). It is not clearly depicted in the figure but there is one soil profile in model 3 which lies in soil class SB classification and two soil profiles lie in soil class SD.

After VS30 and f0 have been determined for each generated soil profile, the next step is to determine the corresponding site amplification factor (FPGA, FA, FV) based on the two approaches: SNI (using VS30) and SAPE (using f0). Table 1 is used for SNI approach, only considering the site factor for the smallest spectral acceleration (linear condition). Equation (1) along with several regression coefficient tables as in Cadet et al (2012) is used for SAPE approach.

Linear viscoelastic site response analysis is then performed for each generated soil profile using a recorded outcropping rock ground motion during Kobe (1995) earthquake, scaled down to PGA of 0.05g to ensure a linear condition. The response spectrum of the calculated motion at ground surface is calculated, and compared with the response spectrum of the input motion at three specific frequencies, correspond to the site factor value of FV, FA, and FPGA. The calculated site factors from site response analysis are then compared with the estimated site factors from both SAPE and SNI approaches. The analysis procedure in this study is better illustrated by the following flowchart as below.

3. RESULTS

The correlation charts between both estimation approaches and the site response result are given in Figure 3 and Figure 4. The observation result from the charts is summarized in this section.

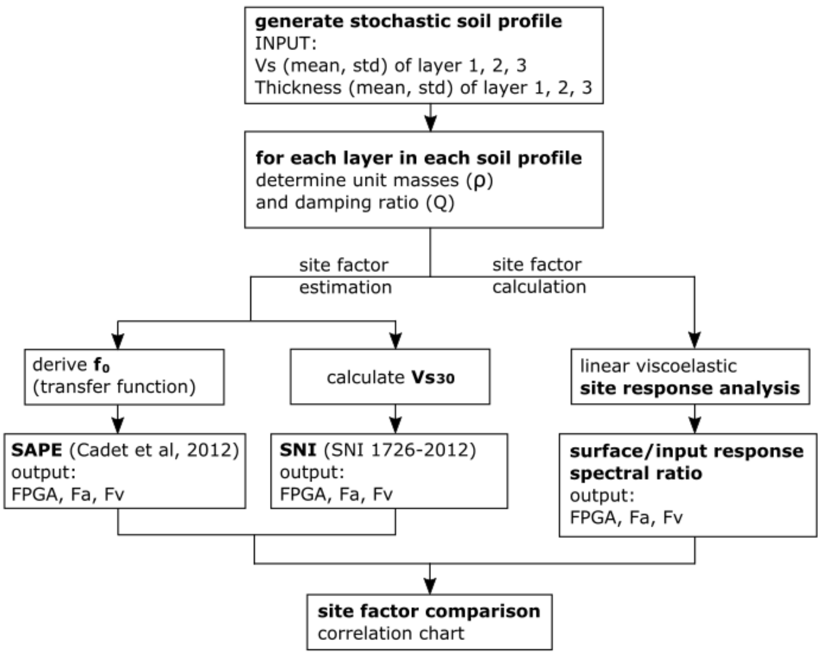


Figure 2 Flowchart of analysis procedure

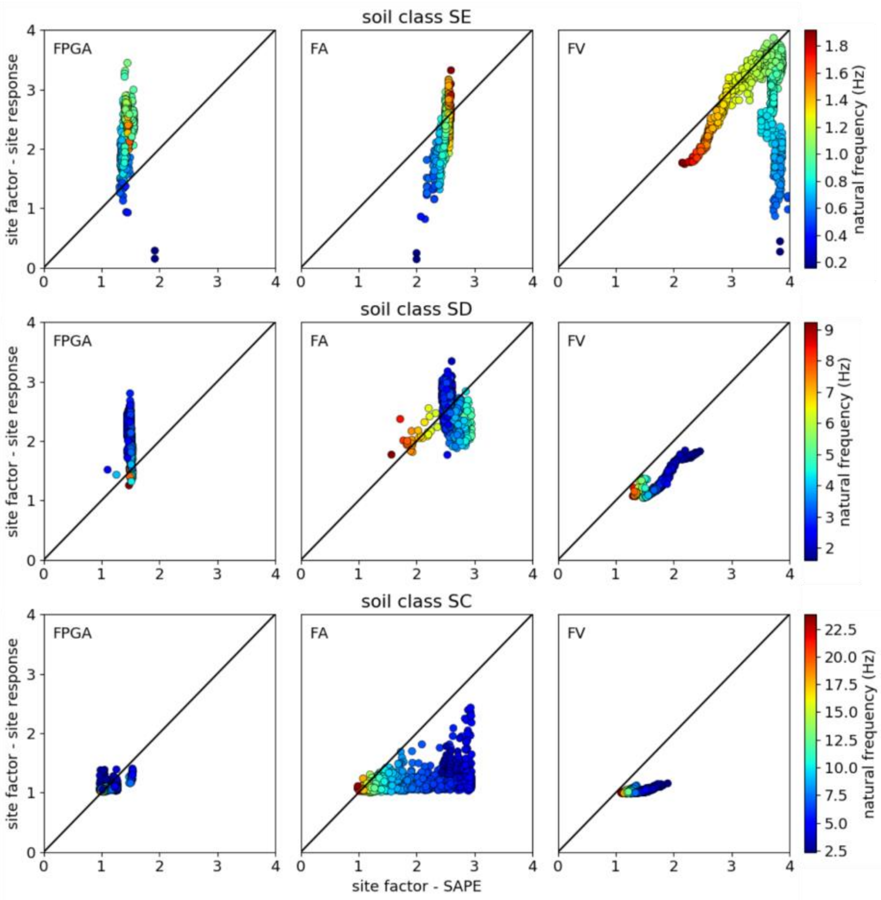


Figure 3 SAPE approach correlation scatter chart for all soil classes

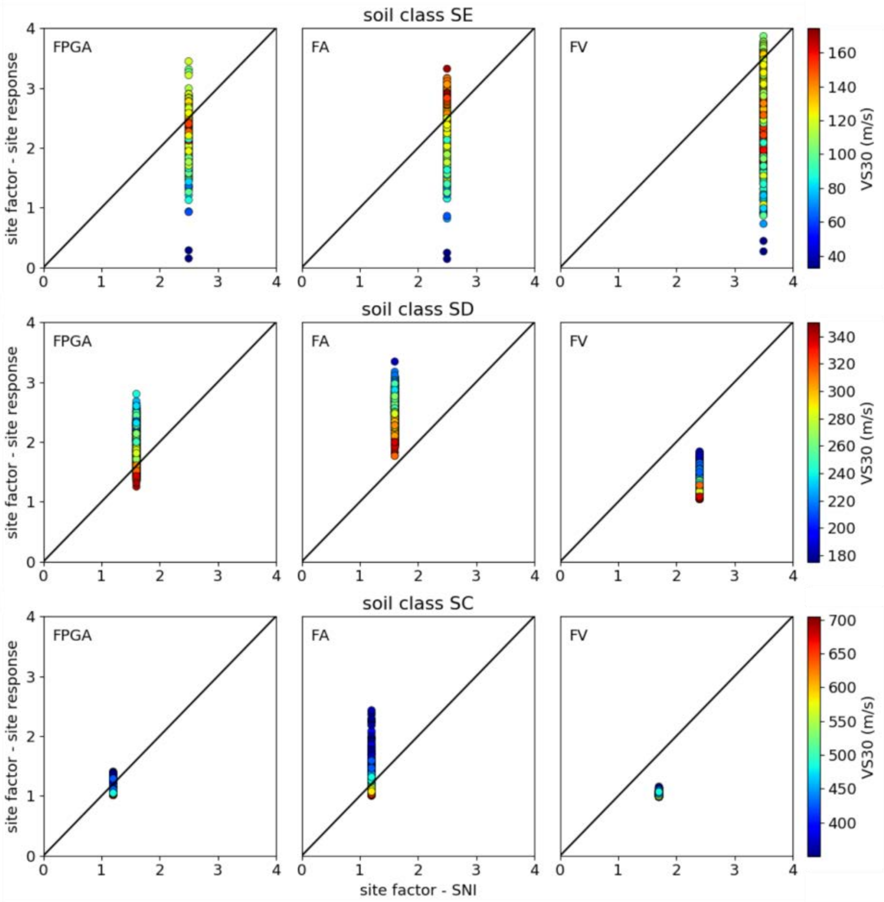


Figure 4 SNI approach correlation scatter chart for all soil classes

3.1 Soil class SE

With the exception of F_V-SAPE, it is clear from the figures above that both approaches do not give a satisfactory correlation with site factors from site response analysis as the scatters are deviating from the correlation line. F_{PGA}-SAPE tends to have a narrow value while the value distribution from the site response is broad. F_A-SAPE has a broader distribution compared to F_{PGA}, but the deviation is still high. One interesting observation is for F_V-SAPE, as the trend and the distribution of the scatter is good for profiles with site frequency (f_0) higher than 1.0 Hz (F_V is in the range of 2.2 - 3.9). For profiles with f_0 lower than 1.0 Hz, the scatter becomes worse and deviating from the correlation line (F_V-SAPE range is narrow, from 3.5-4.0 while F_V-site response has very broad distribution).

F_{PGA}, F_A, F_V determined from SNI all show bad correlation with site response site factor.

3.2 Soil class SD

For this class, F_{PGA}-SAPE has a bad correlation similar to soil class SE. SAPE gives a significantly narrow distribution of F_{PGA} values while site response gives a broader distribution. F_A-SAPE has a good correlation for profiles with f_0 larger than 5 Hz, while the distribution becomes worse for profiles with f_0 lower than 5 Hz. F_V-SAPE in general has a satisfactory correlation, although the scatter slightly deviates from the correlation line, but the trend is good and correlates well with site response F_V. It can be observed that all soil profiles in this model set have f_0 larger than 1 Hz.

Site factors from SNI approach still have bad correlations with site response site factors, however the distribution of site response site factors are now become narrower if compared with the distribution from soil class SE.

3.3 Soil class SC

FPGA-SAPE has a good correlation (values varying between 1.0 - 1.5). A bad correlation is observed for FA-SAPE, since the distribution of FA by the approach is very broad ranging from 1.0 - 3.0 while the site response factor have values ranging from 1.0 - 2.0. Similar to FA, FV-SAPE also seems to overestimate the site response result.

For SNI approach, FPGA has a good correlation while FA underestimate the site response factors. FV-SNI does not give a good result for this soil class since the estimated site factors over-predict the value if compared with site response result.

4. DISCUSSION

Figure 5 below shows an illustration of how SAPE was derived by Cadet et al (2012). As explained above, hundreds of spectral ratio from KIK-Net database was collected and the frequency of each curve is normalized with the natural frequency of the corresponding soil profile, leading to a set of “bell-shaped” curves with maximum amplitude located at abscissa of unity. Then, a correlation is made for natural frequency and its amplification at a specific dimensionless frequency value.

Having that in mind and by observing Figure 5, by logic it is safe to say that the correlation produced for dimensionless frequency less than one (left side of black dashed line) will be better than for dimensionless frequency beyond unity (right side of dashed line). The left side correlation will be better because each curve is always asymptotic at the beginning and eventually reach its maxima at the dashed line, thus the scatter distribution is more regular. On the contrary, for dimensionless frequency larger than one, the scatter distribution is more irregular due to the presence of amplification at higher modes. This will have implication on the quality of the correlation between amplification value and natural frequency.

The explanation above explains Figure 3 on how SAPE performs at a certain frequency (FA / FV / FPGA) in each soil class. For soil class SE, SAPE gives good result for FV only, for sites with f0 larger than 1 Hz. Recall that FV is a site factor at 1 Hz frequency (period 1 sec) and dimensionless frequency is a ratio between the considered frequency of spectral ratio value and the natural frequency of a soil profile (f0). Therefore, the calculated dimensionless frequency for sites with f0 larger than 1 Hz is less than one, thus lies on the left side of the dashed line in Figure 5. Meanwhile, sites with f0 lower than 1 Hz will have dimensionless frequency value which is larger than one, thus plotted in the right side of the dashed line and it explains the bad correlation observed for these soil profiles.

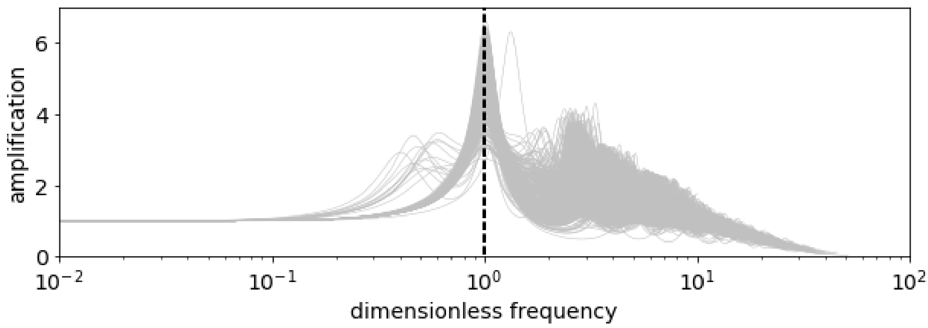


Figure 5 Illustration of normalized transfer function

For soil class SD, SAPE gives good result for FA (frequency 5 Hz; period 0.2 sec) for profiles with f0 larger than 5 Hz. SAPE also performs well for FV (frequency 1 Hz; period 1 sec) since generally all soil profiles in this model set has f0 larger than 1 Hz. For FPGA (frequency 25 Hz, period 0.04 sec), SAPE leads to bad correlation since at this frequency (25 Hz), all soil profiles have dimensionless frequency value greater than one.

By using the same logic as described above, for soil class SC, SAPE should give good result for FA and FV and bad result for FPGA since almost all of the soil profiles have f0 larger than 1 Hz and 5 Hz, but lower than 25 Hz. However the result is the contrary; FPGA has a satisfactory correlation while bad correlation is achieved for FA. The main reason behind this anomaly in SAPE performance might be due to the difficulty in obtaining a good transfer function with a clear amplification by using field instrumentation at rocky sites with high VS30 (soil class SC, SB).

It is confirmed that for “hard soil” sites, a good quality amplification spectrum is really difficult to get either by using geophysical tool (H/V microtremor) or by deriving the spectrum from surface/borehole accelerometer since the impedance contrast between the soil profile and the reference rock site is relatively weak (Pierre-Yves Bard - personal communication). However, despite the bad data scatter of FA-SAPE for this soil class, in fact the FA correlation is satisfactory enough for sites with f0 larger than 15 Hz.

Although the trend of F_V-SAPE correlation for soil class SC seems to be not good enough, the fact that:

1. F_V correlation achieve good result for soil class SE and SD for sites with f_0 larger than 1 Hz, and
2. All soil profiles within soil class SC has f_0 larger than 1 Hz

lead to an argument that in fact F_V -SAPE also performs well for class SC.

The bad correlation of SNI approach as observed for F_{PGA}, F_A, F_V for SE sites explains very well the complexity of a site response at soft soils, which has broad variability and cannot be simplified into a single scalar site factor value (this is also the case for SAPE result). However, it seems that for soil class SD, the correlation is not becoming any better. The SNI site factors achieve satisfactory result for hard soil sites (class SC) for PGA. For F_A, good result is only valid for sites with V_{S30} larger than approximately 450 m/s.

Compared to SAPE site factors for class SC, SNI factors tend to have low value which can be explained by two reasons. First, the reference stations within this soil class, as used by Borcherdt (1994) in his study, is basically consist of hard soils and soft rocks, which eventually will lead to less amplification. Second, as mentioned above, the difficulty of obtaining f_0 in hard soil sites leads to overestimation of site factors. In this case, class SD and SE are the governing soil profiles and lead to correlation bias.

5. CONCLUSION AND RECOMMENDATION

Through stochastic site response analyses performed on varying artificial soil profiles, the application of site factor estimation procedure by V_{S30} (as adopted in SNI 1726-2012) and by f_0 (Cadet et al, 2012) has been compared and several conclusions can be taken as follow:

1. There is no perfect site factor estimation approach. Site proxy is just a proxy of a soil profile, a simple representation of a complex presence. Although it seems that one method outperforms the other, it does not guarantee the reliability of such method since site estimation method always comes with uncertainty (epistemic and aleatory).
2. It appears that SAPE approach is not fully reliable, as it has bad correlation for soft soil sites and for specific spectral acceleration. However, SAPE result is better than SNI approach in several conditions.
3. In-line with the finding of Zhao and Xu (2013) and Cadet et al (2012), natural frequency of a soil profile (f_0) turns out to be a better site proxy compared to V_{S30}. The very root of the reason is because V_{S30} cannot include the effect of deeper soil stratum below 30 m. Furthermore, amplification is also a function of impedance contrast of the soil profile with the underlying halfspace, which makes an even worse estimation for V_{S30} approach for deep-bedrock profiles.
4. The study presented in this paper is only performed for linear condition (low PGA, small strain), therefore non-linearity is not taken into account. The inclusion of such variable will make it more challenging since the uncertainty is increased.

Based on the finding and discussion, a summary table is prepared which consist of suggested approach for different site conditions and different spectral accelerations. The authors hope that this paper can give an insight for practicing engineers and stakeholders, that there is much into it behind the site factors of SNI 1726-2012 as adopted from NEHRP provision 1997. In the end, the selection of any method to estimate site amplification will largely depend on many aspects, e.g. project stage, project budget, project risk, etc.

It is important to note that this table is made solely based on the finding of this study. Improved aspects of this study e.g. more uniform distribution of artificial soil profile, deeper bedrock depth, different method to estimate unit weight and material quality factor, etc may lead to different recommendation as presented herein.

Table 3. Recommended site factor estimation approach based on this study

	soft soil	**medium soil**	**hard soil**
SNI soil class	**SE**	**SD**	**SC**
V_{S30} (m/s)	**< 175**	**175 - 350**	**350 - 750**
f_0 (Hz)	**< 1.8**	**1.8 - 5.6**	**> 3**
F_{PGA}	site response	site response	SNI / SAPE
F_A	site response	site response / SAPE*	SNI / SAPE**
F_V	site response / SAPE***	SAPE	SAPE

*) SAPE is applicable for sites with $f_0 > 5$ Hz
**) SNI is applicable for sites with $V_{S30} > 450$ m/s; SAPE is applicable for sites with $f_0 > 15$ Hz
***) SAPE is applicable for sites with $f_0 > 1$ Hz

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