PSD Wavelet for Attenuation

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Power Spectrum Density of Wavelet (PSDW) Technique for In Situ Measurement of Soil Attenuation Factor

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ABSTRACT: The attenuation factor is one of important parameters used for determining the effects of vibration, from earthquake, machine vibration, and tremors, on the affected soil site. Many studies have been also carried out for determining the attenuation factor and damping behavior. Empirical correlations between the damping ratio in terms of attenuation and the amount of radiated energy compared to the frequency of vibration and type of soil have also been continuously investigated. The aim of this paper is to introduce a new approach of the power spectrum density of wavelet (PSDW) analysis of seismic waves to determine the attenuation factor on the soil structures. The attenuation factor is measured from the radiation of seismic wave propagation on the sub-surface. This method improves a commonly used attenuation analysis using Fourier analysis as a basis of calculation. Fourier analysis has a lack of accurate identification for certain characteristic features occur in a waveform. As Fourier basis functions are localized in frequency but not in time base. The results show that by using PSDW technique, the time-frequency of wavelet density spectrum is able to increase flexibility as both traditional time and frequency domain system identification approaches can be exploited to examine nonlinear seismic events in the attenuation analysis. An empirical correlation of frequency-independent attenuation factor was obtained from the PSDW analysis. Good agreement was also found between the values of the soil attenuation obtained in this study compared to that of other researchers.

Keywords: wavelet; power spectrum density; attenuation

1 INTRODUCTION

Soil attenuation is one of important parameters in geo-earthquake engineering problems associated with dynamic loading at low to moderate-strain levels, e.g., ground amplification during earthquake (Vucetic & Dobry, 1991). The attenuation parameter of soil can be either determined from the radiation and material damping of the soil structure. Attenuation in soil dynamics is a phenomenon that involves the interaction of several mechanisms that contributed to the energy dissipation of the seismic wave during dynamic excitation (Rix et al., 2000). The parameter can be in situ evaluated by using seismic methods, i.e., measurement of wave velocities propagating through soil medium. The spectral analysis of surface wave (SASW) is one of common seismic techniques used for this purpose. Much of the basis of the theoretical and analytical work of this method for soil investigation has been developed. Current developments of the SASW method can be found in Rosyidi (2009).

Many in situ and laboratory tests have been used to evaluate attenuation parameter. Rix et al. (2000) investigated surface wave measurements to determine the attenuation and damping ratio of a layered soil deposit. In their studies, an attenuation curve was constructed from the observed spatial attenuation of Rayleigh wave amplitudes and then was inverted to obtain the material shear damping ratio. However, seismic data used in surface wave analysis are non-stationary in nature i.e. varying frequency content in time. Fourier transform that usually used by many researchers in seismic measurements works by expressing any arbitrary periodic function of time with period as sum a set of sinusoidal, thus some information of non-stationary seismic data in analysis maybe lost. In addition, the inability of conventional Fourier analysis to preserve the time dependence and describe the evolutionary spectral characteristics of non-stationary processes require tools which allow time and frequency localization beyond customary Fourier analysis. Wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series. By decomposing a time series into time-frequency spectrum (TFW), one is able to determine both the dominant modes of variability and how those modes vary in time. The wavelet analysis has been used in numerous studies in geotechnical investigation, i.e., in situ shear modulus (Rosyidi, 2009), phase velocity of soil structures (Kim & Park, 2002), soil damping ratio (Rosyidi & Taha, 2012).

The objective of this paper is to present the novel approach of the power spectrum density of wavelet (PSDW) analysis of seismic waves based on mother wavelet of Morlet used to evaluate in-situ attenuation factor of soil structures. Result and its application from field study carried out at unsatured soft soil site are also presented.

2 RESEARCH METHODOLOGY

2.1 *Wavelet Analysis*

A wavelet is defined as a function of $\psi(t) \in L^2(\Re)$ with a zero mean, which is localized in both time and frequency. By dilating and translating the wavelet $\psi(t)$, a family of wavelets can be produced as:

$$\psi_{\sigma,\tau}(\tau) = \frac{1}{\sqrt{\sigma}}\psi\left(\frac{t-\tau}{\sigma}\right) \tag{1}$$

where σ is the dilation parameter or scale and τ is the translation parameter ($\sigma, \tau \in \Re$ and $\sigma \neq 0$)

The CWT is defined as the inner product of the family wavelets $\Psi_{\sigma,\tau}(t)$ with the signal of $f(t)$ which is given as:

$$F_W(\sigma,\tau) = \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{\sigma}}\overline{\psi}\left(\frac{t-\tau}{\sigma}\right)dt \tag{2}$$

where $\overline{\psi}$ is the complex conjugate of ψ and $F_W(\sigma,\tau)$ is the time-scale map. The convolution integral from equation 2 can be computed in the Fourier domain. To reconstruct the function $f(t)$ from the wavelet transform, Calderon's identify (Daubechies, 1992) can be used and is obtained as:

$$f(t) = \frac{1}{C_\psi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F_W(\sigma,\tau)\psi\left(\frac{t-\tau}{\sigma}\right)\frac{d\sigma}{\sigma^2}\frac{d\tau}{\sqrt{\sigma}} \tag{3}$$

$$C_\psi = 2\pi\int\frac{|\hat{\psi}(\omega)|^2}{\omega}d\omega < \infty \tag{4}$$

where $\hat{\psi}(\omega)$ is the Fourier transform of $\psi(t)$. The integrand in equation 4 has an integrable discontinuity at ω 0 and implies that $\int\psi(t)dt = 0$.

2.2 *Power Spectrum Density of Wavelet (PSDW) Transform*

The total energy contained in a signal, $x(t)$, is defined its integrated squared magnitude as follows:

$$E = \int_{-\infty}^{\infty}|x(t)|^2 dt$$

The relative contribution of the signal energy contai at a specific σ scale and τ location in the CWT is gi by the two-dimensional wavelet energy density functi

$$P_{F_w}(u,\xi) = |F_w(\sigma,\tau)|^2 \tag{5}$$

A plot of P_{Fw} is known as a scalogram which is analogous to the spectrogram and the power spectrum density (PSD) surface of the STFT (short-time-Fourier-transform). The scalogram can be integrated across σ and τ to recover the total energy in the signal as follows:

$$P_{F_w} = \frac{1}{C_g}\int_{-\infty}^{\infty}\int_{0}^{\infty} P_{F_w}(\sigma,\tau)\frac{d\sigma}{\sigma^2}d\tau \tag{7}$$

where C_g is the admissibility constant of the wavelet function $\psi(t)$.

2.3 *Proposed Procedure for Attenuation Analysis*

A proposed procedure used in attenuation analysis of soil structures is described in Figure 2 as follows.

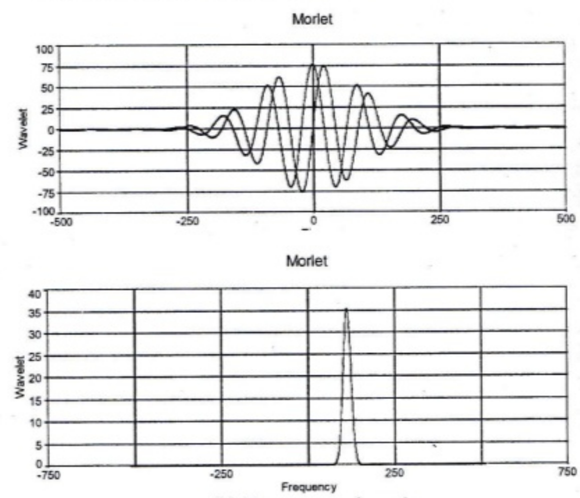
1. Select the wavelet function and a set of scale, s, to be used in the wavelet transform. The different wavelet function may influence the time and frequency resolution. In this study, a Morlet wavelet function was selected as a mother wavelet in the CWT analysis.

   A commonly used wavelet in CWT is the Morlet wavelet where its shape is a Gaussian-windowed complex sinusoid. It is defined in the time and frequency domains as follows:

$$\Psi_0(t) = \pi^{-1/4}e^{imt}e^{-t^2/2} \tag{8}$$

$$\hat{\psi}_0(s\omega) = \pi^{-1/4}H(\omega)e^{-(s\omega-m)^2/2} \tag{9}$$

where m is the wavenumber, and H is the Heaviside function. The time and frequency domain plot of Morlet wavelet is shown in Figure 2. In Figure 2a, the Morlet wavelet is shown within an adjustable parameter m of 7 which is used in this study. This parameter can be used for an accurate signal reconstruction of seismic surface waves in low frequency. The Gaussian's second order exponential decay used in time resolution plot results in the best time localization.



(b) Frequency domain

Figure 1. Time and frequency domain plot of Morlet wavelet

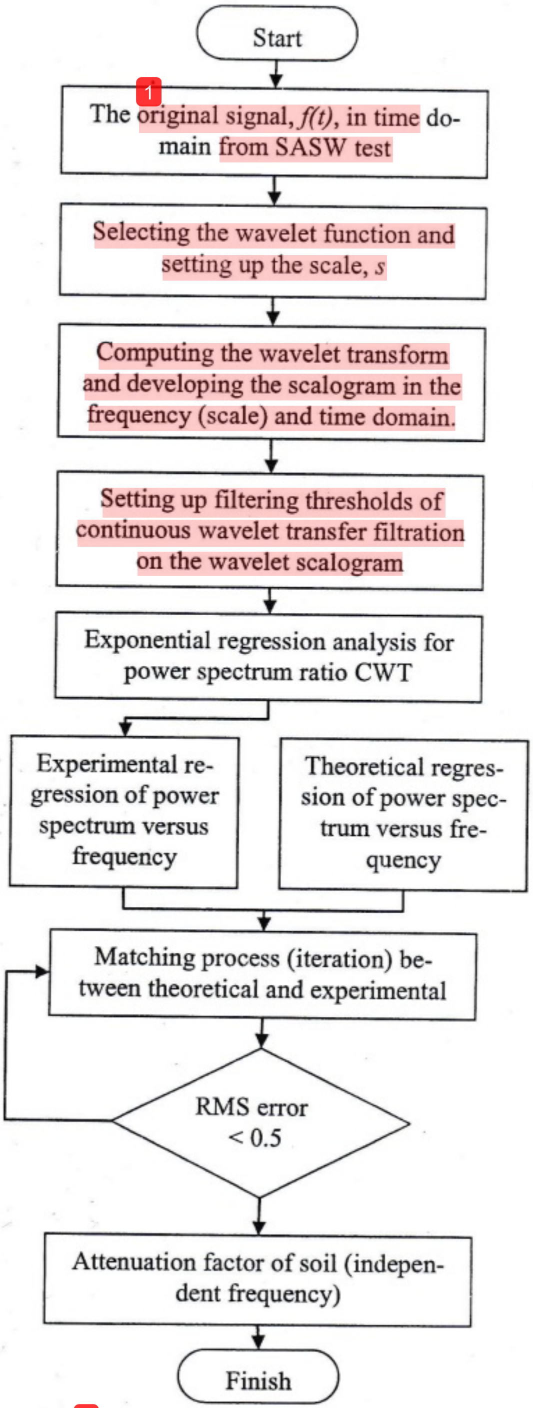


Figure 2. Flow chart of CWT Filtering procedure.

2. Develop the wavelet scalogram by implementing the wavelet transform (equation 2) using computed convolution of the seismic trace with a scaled wavelet dictionary. Wavelet scale is calculated as fractional power of 2 using the formulation (Torrence & Compo, 1998):

$$s_j = s_0 2^{j\delta_j}, j = 0, 1, ..., J \qquad (10)$$

$$J = \delta j^{-1} \log_2\left(\frac{N\delta_t}{s_0}\right) \qquad (11)$$

where, s_0 is smallest resolvable scale = $2\delta_t$, δ_t is time spacing, and J is largest scale.

3. Convert the scale dependent wavelet energy spectrum (scalogram) or power spectrum density of the signal to a frequency dependent wavelet energy spectrogram in order to compare directly with Fourier energy spectrum.
4. Perform the CWT filtration on the wavelet spectrogram by obtaining the time and frequency localization thresholds. In this study, the CWT filtration was developed by a simple truncation filter concept which only considers the passband and stopband. Threshold values in time and frequency domain are then set as the filter values between passband and stopband. It allows a straight filtering in each of the dimensions of times, frequencies and spectral energy. The noisy or unnecessary signals can be eliminated by zeroing the spectrum energy and consequently, they are fully removed when reconstructing the time domain signal. Thus, the interested spectrum of signals are to be passed when the spectrum energy is maintained in original value. A design of the CWT filtration is proposed by Rosyidi (2009).
5. Reconstruct the time series of seismic trace using equation 3 and generate the power spectrum density of wavelet or spectrogram from denoised signals.
6. Generate PSDW ratio from both signals as experimental power spectrum ratio versus frequency using the linear regression.
7. Generate the theoretical regression of PSDW ratio versus frequency using following equation (Rosyidi & Taha, 2012):

$$\ln\left[\frac{W_f^{R_2}(\sigma,\tau)}{W_f^{R_1}(\sigma,\tau)}\right] = \ln\left\{\left(\frac{R_1}{R_2}\right)^n \cdot G(R)\cdot G(I)\cdot K(R)\right\} - \alpha(f)(R_1 - R_2) \qquad (12)$$

$$\ln\left[\frac{W_f^{R_2}(\sigma,\tau)}{W_f^{R_1}(\sigma,\tau)}\right] = k - \alpha(f)(\Delta R) \qquad (13)$$

where, R_1 and R_2 are geophones distance from the sources (if using two geophones), $G(R)$ is geometric spreading factor, $G(I)$ is instrumentation correction factor and $K(R)$ is correction for refracted and transmitted waves, α is independent frequency-attenuation factor.

8. Finally, by matching the data of theoretical to the experimental regression line, the attenuation factor of soil structures can be obtained. By repeating the procedure outlined above the attenuation factor corresponding to each wavelength is subsequently generated.

2.4 *Field procedure of surface wave measurement*

In this study, the spectral analysis of surface wave method was employed to collect the seismic surface wave data for soil dynamic evaluation. A configuration set up on the SASW measurement is shown in Figure 3. An impact source of 8 to 12 kg was used to generate seismic waves. These waves were then received using two 1-Hz frequency natural vertical geophones. Thus, they were recorded by using a set of spectrum analyser for processing (Figure 3).

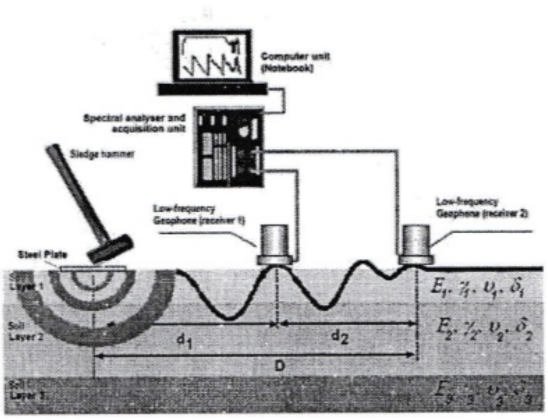


Figure 3. SASW measurement set up applied on the soil sites (Rosyidi & Taha, 2010)

Several configurations at 1, 2, 4, 8 m of the receiver and the source spacings were required in order to sample different soil depths. The configuration used in this measurement was the mid-point receiver spacings. In this configuration, the short receiver spacings with a high frequency source were used to sample the shallow layers of the soil profile while the larger receiver spacings with a set of low frequency sources were employed to sample the deeper layers.

3 RESULTS AND DISCUSSION

3.1 *Residual Soil Properties*

The tests were carried out in a fairly flat field at Radio Television Malaysia (RTM) compound in Kelang, Malaysia. The soil descriptions from the site have shown that the soil type is greyish clay with decayed wood at most of the soil layers of the subsoil stratum. Based on geological data, the site was classified as recent quaternary of dominantly alluvial deposits of soft marine clay with traces of organics.

3.2 *Response Spectrum and Power Spectrum Density*

Figure 4 shows the recorded signals from multiple impacts of a source. The seismic data was recorded using field configuration of 8 m receivers (geophones) spacing. From the recorded signals, it can be recognized that higher amplitude is measured for first mode of R-wave amplitude. It is also noted that the decreasing signal magnitude is identified as the R-wave attenuation in the soil layer which is an important characteristic for energy decrement. The waveform of seismic signal recorded in measurement is transient and non-stationary event. Weak recorded signal of seismic wave particularly in channel 2 is also identified as an effect of environmental noise which maybe produced from ground noise and man-made vibration. This means that either the input signals or behaviours of system at different moments in time were not identical. When the signals were transformed into frequency domain (Figure 5), time-dependent behaviour of the seismic waves and noise events vanished. In the energy content which these events present at different times and frequency, would not be picked up by a conventional Fourier analysis. It also cannot instantly separate the event of true seismic waves from noise signals. Consequently, it is difficult to interpret the correct energy of waves in both signals.

The time-frequency (TF) analysis of CWT was then employed to overcome the identification problem of spectral characteristic of non-stationary seismic wave signals and conduct the filtration analysis to reconstruct the interested signals from measurement. Filtration technique used in this analysis was recommended by Rosyidi (2009) which is based on time-frequency thresholds. The technique can identify and remove the noise spectrum from the recorded signals. Denoising and cleaning noise signals are possible to improve the clarity of response spectrum analysis.

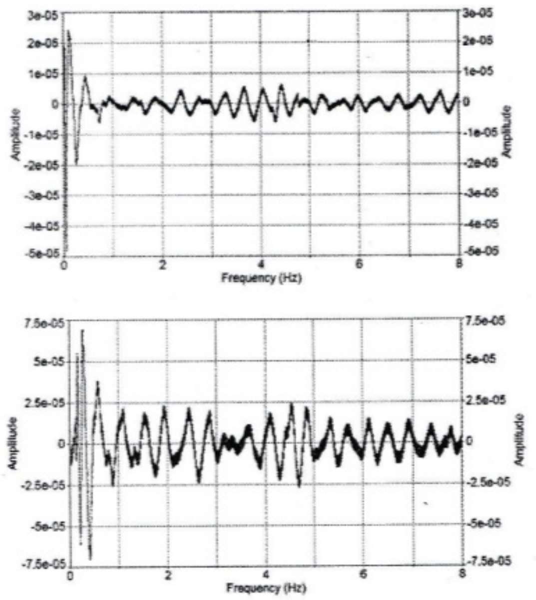


Figure 4. Seismic surface wave signals recorded from two channels of geophone.

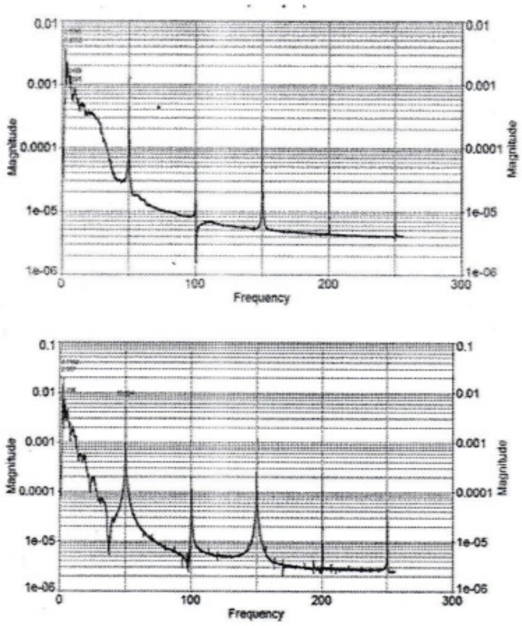
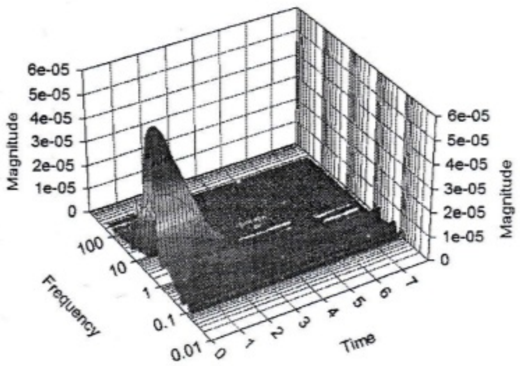


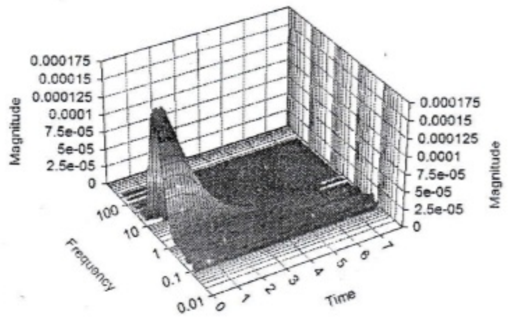
Figure 5. Fourier amplitude from both signals.

There are two primary ways to set the thresholds for wavelet filtering. The first is to define a region of time-frequency space. This is primarily used to isolate and reconstruct signal components. The time and frequency fields define limits in spectrogram filtering. In this study, the frequency range of noise signal was set as threshold of wavelet filtering. It means that the noise signals are removed from the spectrogram and only seismic wave signals of interested exist. The inverse wavelet transform then give back a denoised seismic signal. The power spectrum density of wavelet or spectrogram for both denoising signals is shown in Figure 6.

The spectrum range of the seismic waves of interest was found in the range of 5 to 30 Hz and 5 to 35 Hz for signals recorded on channel 1 and 2, respectively. The energy attenuation is also visibly identified from both spectrums.



(a). Signal from channel 1



(b). Signal from channel 2

Figure 6. Power spectrum density of wavelet or spectrogram from both denoised signals.

3.3 *Attenuation Analysis based on Power Spectrum Density*

From Figure 6, an experimental data trend of power spectrum ratio between both signals from logarithmic natural (LN) function of spectrogram (w_2) over the first signal magnitude (w_1) versus frequency can be obtained. This ratio represents as the decay factor curve of frequency dependency from the R-wave motion (Figure 7). A simple linear regression analysis is subsequently performed on the experimental data of decay factor curve. The experimental regression equation is produced as:

$$\ln\left[\frac{W_f^{R_2}(u,s)}{W_f^{R_1}(u,s)}\right] = -0.0244(f)+2.3025 \qquad (14)$$

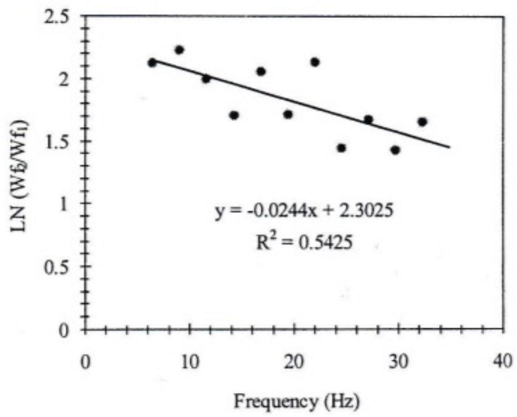


Figure 7. Regression analysis of attenuation coefficient of the soil from power spectrum density of wavelet (Figure 6).

The theoretical regression analysis of attenuation derived from Eq. 13 can then be written as:

$$\ln\left[\frac{W_f^{R_2}(u,s)}{W_f^{R_1}(u,s)}\right] = -\alpha(f)(\Delta R)+k \\ = -8\alpha_0(f)+k \quad (15)$$

The best-fit curve is then established between the decay factor of the experimental data (Eq. 14) and the theoretical regression analysis equation (Eq. 15) by trial and error for different values of α_0 from visual best-fit evaluation of the two curves. The best-fit value of frequency-independent attenuation coefficient of the soil is calculated as 3.05×10^{-3} s/m at frequency of 5 to 35 Hz. The root mean square error for this fitting curve is found to be 0.2.

The values of the frequency-independent attenuation coefficient obtained from this study and the average shear wave velocity at soil site obtained by Rosyidi & Taha (2012) were compared with experimental results that have been carried out by other researchers, such as Yang (1995), Woods (1997), Athanasopoulos et al. (2000) and Rosyidi et al. (2008) as shown in Figure 8. Woods and Jedele (1985) classified soil groups from the frequency-dependent attenuation of the 5 Hz vibration. The attenuation factor of unsaturated soft soil from this study falls into Class 1 (soft soil) using Woods and Jedele (1985) classification. In general, the results are also in good agreement with Anthanasopoulos et al. (2000) that developed the range of attenuation coefficient for soils. The attenuation coefficient obtained in this study is still within the upper and lower bound of the Anthanasopoulos's (2000):

$$\alpha_0 = 3.17 \times 10^{-3} \times e^{-\frac{Vs}{500}} \text{ (best-fit)} \quad (16)$$

$$\alpha_0 = 1.15 \times 10^{-3} \times e^{-\frac{Vs}{500}} \text{ (lower bound)} \quad (17)$$

Rosyidi et al (2008) observed soil attenuation coefficient of the subgrade material using the spectral analysis of surface waves (SASW) method. From their study, the average attenuation of residual soil subgrade was found 1.58 × 10-3 s/m ranging between 1.018 – 2.145 × 10-3 s/m. The result can be classified into Class 1 (soft soil).

Comparing to study conducted by Yang (1995) which also studied the frequency-independent attenuation coefficient for soil ranging from loose sand and soft clays to rock. Figure 8 shows that the attenuation factor of this study is close to the upper bound of the attenuation coefficient range obtained by Yang (1995) for unsaturated loose sand material which is most likely due to the difference in material.

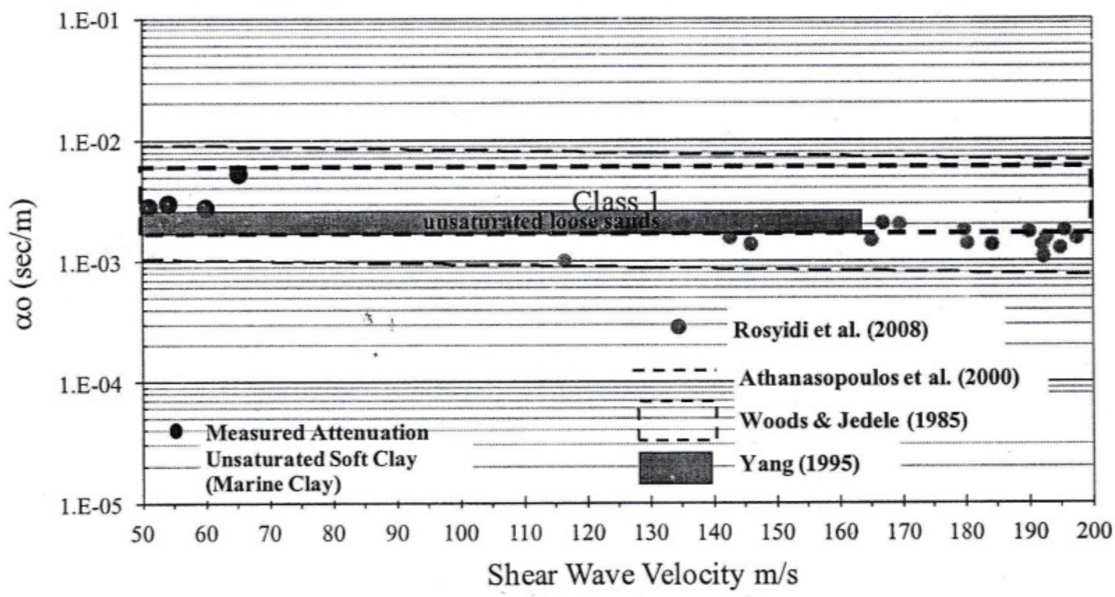


Figure 8. Attenuation factor of unsaturated soft soil from this study compared to the attenuation curve from other researchers.

4 CONCLUSIONS

In general, the power spectrum density of wavelet technique for attenuation analysis of soil structures was proposed in this study. A good agreement was obtained between the attenuation factor obtained from this study compared to the studies of Yang (1995), Woods & Jedele (1985), Athanasopoulos. et al. (2000) and Rosyidi et al. (2008).

The value of attenuation factor of the soft soil layer obtained from PSDW technique also shows good agreement and falls into the classification of soft soil attenuation by Woods and Jedele (1985).

Thus, it is shown that the characterization of the physical properties of the soil dynamics in terms of attenuation coefficient can be satisfactory obtained using the PSDW method. In addition, this method has the advantage of being fast, economical and non-destructive.

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