Attenuation Analysis On Soil Structure Based On Wavelet Spectrogram

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ATTENUATION ANALYSIS ON SOIL STRUCTURE BASED ON WAVELET SPECTROGRAM (116G)

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ABSTRACT

Many problems related to geotechnical structures, the wave attenuation is useful for determining the effects of vibration on the affected area. Many studies have been also conducted to obtain the damping and empirical correlations between the damping ratio in term attenuation and the amount of radiated energy compared to the frequency of vibration and type of soil. The aim of this paper is to determine the frequency-independent attenuation coefficient generated Rayleigh wave on soil medium using a wavelet spectrogram analysis. This method improves a common used signal processing tools, e.g., Fourier analysis, for attenuation analyses which fail to identify when certain characteristic features occur in a waveform. The time-frequency character of wavelet transforms allows increased flexibility as both traditional time and frequency domain system identification approaches can be exploited to examine nonlinear and nonstationary seismic events that are in essence obscured by traditional spectral approaches. A frequency-independent attenuation empirical coefficient was obtained from wavelet spectrogram analysis. This study is conducted to show the capability of wavelet spectrogram analysis for attenuation measurement of soil layer profile.

Keywords: attenuation, soil structure, wavelet

1. INTRODUCTION

The attenuation parameter of soil is either determined from the radiation and material damping of the soil structure. This parameter is one of important parameters which measure ground amplification during earthquake (Vucetic and Dobry, 1991). 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 physical mechanism that has been postulated to be responsible for attenuation and soil damping is the energy loss in materials, for instance, the frictional losses between soil particles. The damping ratio (*D*) is defined as the ratio between the energy loss and a maximum stored energy within one loading-cycle (Figure 1). Under the low-loss condition, the relationship between quantities used in different disciplines to characterize fundamental attenuation and material damping follows:

$$Q^{-1} = 2D = \frac{\Delta E}{2\pi E} \qquad (1)$$

where Q^{-1} is the dissipation factor which describes as material attenuation, ΔE energy dissipated during one cycle at circular frequency ω and *E* the maximum strain energy stored during referred cycle. Aki & Richards (1980) mentioned that *D* behaved as frequency independent for $0.1 < f < 10$ Hz which is also called hysteretic or rate-independent damping. Material damping can also be obtained using the attenuation coefficient (α) and the logarithmic decrement (δ) in which their relationship is written as:

$$D = \frac{\alpha c}{\omega - \dfrac{\alpha^2 c^2}{\omega}} = \frac{\delta}{2\pi}\frac{1}{\sqrt{1+\left(\dfrac{\delta}{2\pi}\right)^2}} \qquad (2)$$

where *c* is seismic wave velocity. The damping ratio during dynamic excitation is usually a small value (less than 10 %), consequently the second order terms are negligible and Eq. (2) can be rewritten as:

$$D = \frac{\alpha c}{\omega} = \frac{\delta}{2\pi} \tag{3}$$

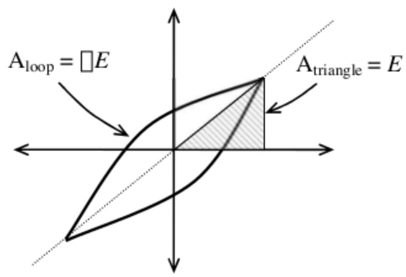


Figure 1. Damping obtained from the cyclic shear stress – strain curve (Rosyidi et al., 2008).

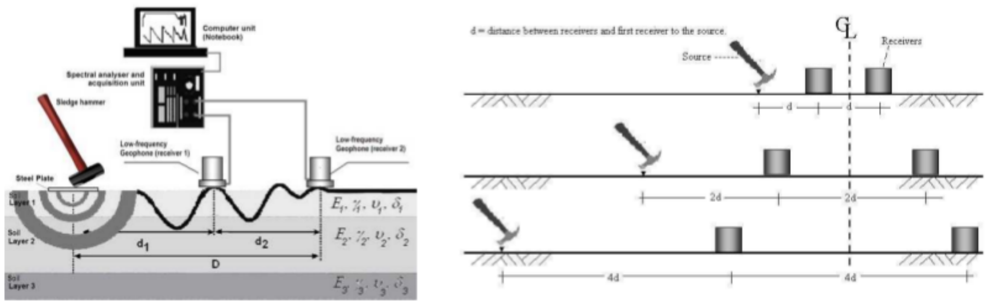
Other physical mechanisms also contributed to the decay in the seismic wave amplitude that propagates in the soil mass. The first mechanism is the spreading of energy over an expanding area as the wavefront propagates away from the source causing the amplitude of waves to attenuate with increasing distance from the source (geometric or radiation damping). The second mechanism explained that the reflection and transmission of seismic waves at inter-faces, mode conversions and scattering in non-homogeneous media causes the wave amplitude to diminish (Rix et al., 2000).

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. Time-frequency decomposition of a seismic signal aims to characterise the phase information of transfer function spectrum. 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. Studies on the improvement of attenuation analysis obtained from in situ measurements of seismic wave attenuation were relatively few. Therefore, this paper is aimed to determine the attenuation coefficient ($\square_0$) from Rayleigh wave (*R*-wave) measurement on the soil structure using the wavelet analysis.

2. RESEARCH METHOD

Field Test Set Up

Two key elements of the surface wave method are the generation of surface wave energy from impact sources and the measurement of the particle motion of the *R*-wave at suitable distances from the source on the surface of media. In layered soil media, the surface wave velocity depends on the frequency (or wavelength) of the wave. The variation of the velocity with frequency is called dispersion and arises due to the different wavelengths of waves passing through the layered media. Short wavelengths (high frequency) of waves propagate only through near-surface materials while longer wavelengths (lower frequency) of waves propagate in deeper layers. A plot of surface (*R*-) wave velocity versus frequency is called the dispersion curve. The experimental set up of the surface wave test is shown in Figure 2(a). *R*-waves in field tests were detected using two geophones. Several configurations of the geophones and the source spacings were required in order to sample different depths. Short receiver spacings with frequency sources were used to sample the surface layer of soil structure while larger receiver spacings with low frequency sources were implemented to sample the deeper layers. The arrangement of receivers which was adopted in this study is the common receiver midpoint geometry as illustrated in Figure 2(b). The surface wave test was carried out at some different sites on soft soil at Kelang, Malaysia.



(a) (b)

Figure 2. Field set up of SASW measurement (a) (Rosyidi & Taha, 2012) and its arrangement of receivers (b)

Wavelet Spectrogram Analysis

The signals produced from impact sources in time domain are digitalised and recorded in time domain by a dynamic spectral analyser. In order to measure the attenuation data from signals recorded from field measurement, the spectrogram attenuation model developed by Rosyidi (2009) and Rosyidi & Taha (2012) was employed in the analysis. The decrease in amplitude (energy density) of the vertical component of the R-wave with distance due only to geometric configuration is also called the radiation damping or geometric spreading. An effective soil damping ratio of R-wave in layered medium can be defined from the attenuation analysis and the value is frequency dependent. Its value may become very high for the first few modes of vibration. The attenuation data (α) of R-wave can be performed by the spectrogram attenuation model proposed by Rosyidi (2009) as follows:

$$\ln\left[\frac{W_f^{R_2}(u,s)}{W_f^{R_1}(u,s)}\right] = \ln\left[\left\{\frac{R_1}{R_2}\right\}^n \left\{G(R)\cdot G(I)\cdot K(R)\right\} e^{\{-\alpha(f)(R_1-R_2)\}}\right] \quad (4)$$

where, R_1 dan R_2 = geophones distance from the sources (if using two geophones), $W_f^{R_1}(u,s)$ dan $W_f^{R_2}(u,s)$= spectrogram magnitude response of wavelet for geophone 1 and 2 respectively, $G(R)$ = geometric spreading factor, $G(I)$ = instrumentation correction factor and $K(R)$ = correction for refracted and transmitted waves.

A spectrogram magnitude response produced from wavelet analysis 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:

$$\psi_{\sigma,\tau}(\tau) = \frac{1}{\sqrt{\sigma}}\psi\left(\frac{t-\tau}{\sigma}\right) \quad (5)$$

where σ is the dilation parameter or scale and τ is the translation parameter (σ, $\tau \in \Re$ and $\sigma \neq 0$). The continuous wavelet transform (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:

$$F_W(\sigma,\tau) = \langle f(t), \psi_{\sigma,\tau}(t)\rangle = \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{\sigma}}\bar{\psi}\left(\frac{t-\tau}{\sigma}\right)dt \quad (6)$$

where $\bar{\psi}$ is the complex conjugate of ψ and $F_W(\sigma,\tau)$ is the time-scale map. The convolution integral from Eq. (6) 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:

$$f(t)=\frac{1}{C_{\psi}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}F_{W}(\sigma,\tau)\psi\left(\frac{t-\tau}{\sigma}\right)\frac{d\sigma}{\sigma^{2}}\frac{d\tau}{\sqrt{\sigma}} \tag{7}$$

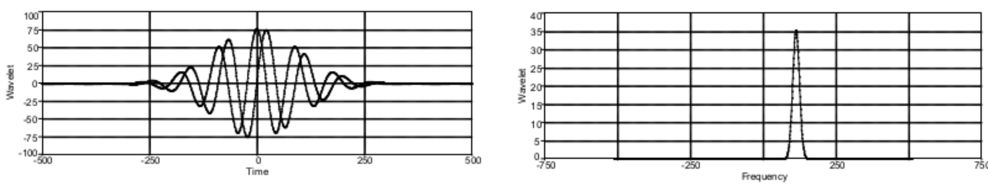
$$C_{\psi}=2\pi\int\frac{\left|\hat{\psi}(\omega)\right|^{2}}{\omega}d\omega<\infty \tag{8}$$

where $\hat{\psi}(\omega)$ is the Fourier transform of $\psi(t)$. The integrand in Eq. (8) has an integrable discontinuity at $\omega = 0$ and implies that $\int\psi(t)dt=0$. 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:

$$\Psi_{0}(t)=\pi^{-1/4}e^{imt}e^{-t^{2}/2} \tag{9}$$

$$\hat{\psi}_{0}(s\omega)=\pi^{-1/4}H(\omega)e^{-(s\omega-m)^{2}/2} \tag{10}$$

where m is the wavenumber, and H is the Heaviside function. The time and frequency domain plot of Morlet wavelet is shown in Figure 3. 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.



(a) (b)

Figure 3. Time domain of real and imaginary part (a) and frequency domain plot of Morlet (b)

3. RESULTS AND DISCUSSION

Figure 4 shows the wavelet spectrogram generated from Morlet wavelet analysis on 1 and 2 m receiver spacing for signal measurement received by geophone 1 and 2, respectively. From both spectrograms, a plot of ratio between the second signal magnitudes from 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 5). A simple regression analysis is subsequently performed on the experimental data of decay factor curve. The theoretical regression analysis of attenuation derived from Eq. (4) can then be written as:

$$\ln\left[\frac{W_{f}^{R_2}(u,s)}{W_{f}^{R_1}(u,s)}\right]=-\alpha(f)(\square R)+k=-2\alpha_{0}(f)+k \tag{6}$$

The best-fit curve is then established between the decay factor of the experimental data and the regression analysis equation by trial and error for different values of α_0 from visual best-fit evaluation of the two curves. From Figure 5, the best-fit value of frequency-independent attenuation coefficient of the soil is calculated as 5×10^{-3} s/m at frequency of 3 to 20 Hz. The frequency range of the attenuation coefficient of the R-waves in the pavement layers was chosen using the bandwidth criteria. The root mean square error for this fitting curve is found to be 0.27.

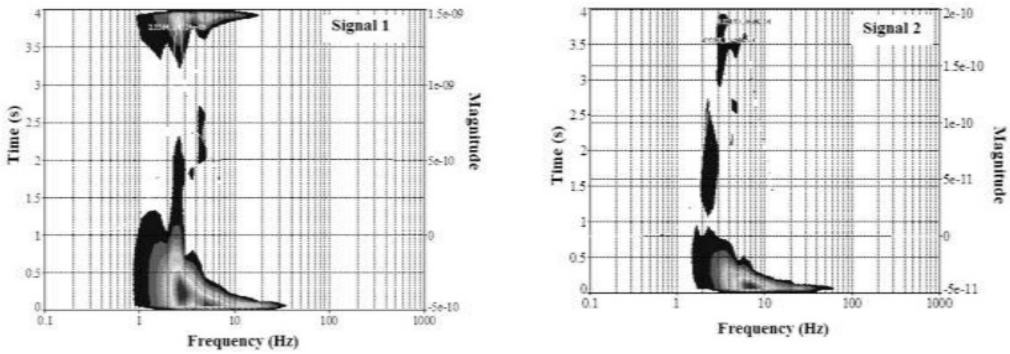


Figure 4. The wavelet spectrogram of signals received by geophone 1 and 2.

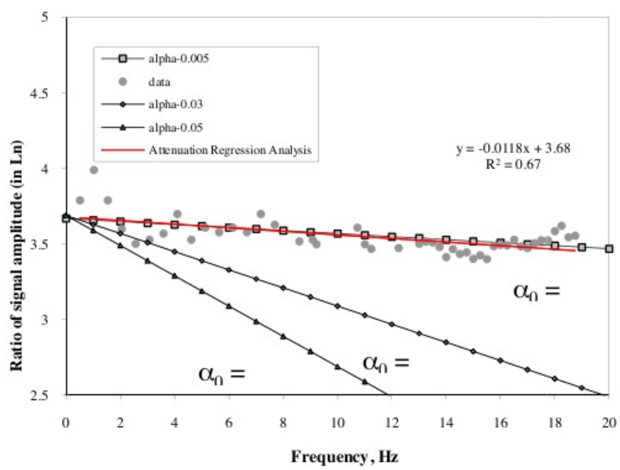


Figure 5. The best-fit frequency-independent attenuation coefficient of the soil based on regression analysis

By repeating the procedure for attenuation analysis in each frequency value for all seismic data, the experimental attenuation curve is subsequently generated. An example of attenuation versus frequency curve at the soil site is presented in Figure 6a. By knowing the experimental attenuation profile, the shear damping ratio can be obtained by inversion process.

In the inversion analysis, the soil model is typically assumed as the homogeneous linear elastic layers over a half-space with model parameter of shear wave velocity, shear damping ratio and thickness for each layer. In this study, due to shear damping ratio is unknown data and there is no prior information from the previous field or laboratory soil data, therefore, it should be assumed with rational values for soil model parameter. The inversion analysis is processed by using Herrmann (1994) code based on a weighted, damped, least-squares algorithm. Figure 6b shows comparisons between the experimental attenuation curves and the theoretical attenuation data. Iteration processes were conducted to match between both experimental and theoretical curves. Figure 7 presents the final profiles of shear damping ratio for the last iteration of the inversion process with lowest RMS error.

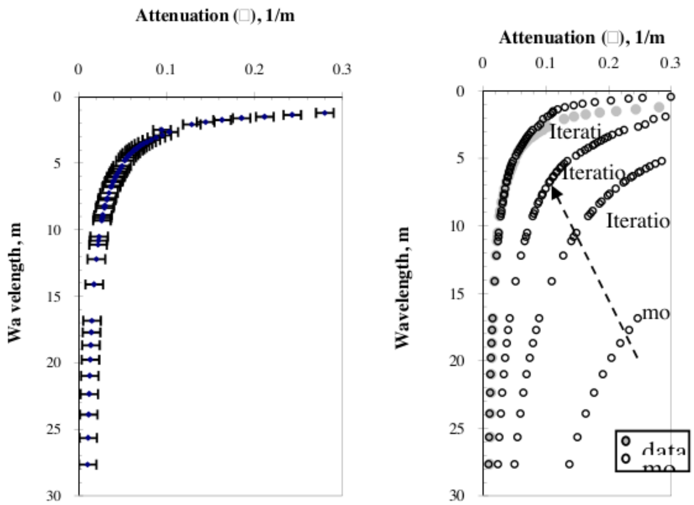


Figure 6 (a) Experimental attenuation versus frequency curve at the soil site and (b). iteration process in the inversion analysis for fitting of theoretical attenuation curve to the experimental curve.

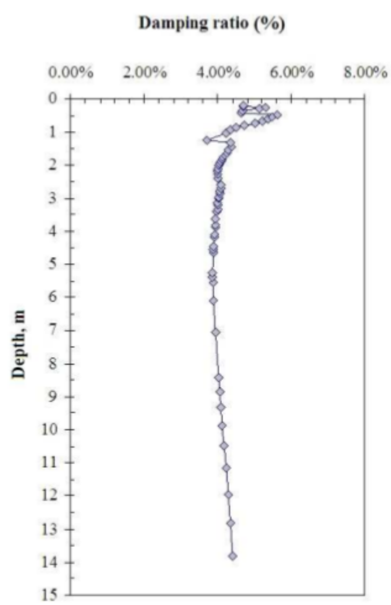


Figure 7. Final damping ratio profile from inversion analysis of attenuation curve from Fig. 6

4. CONCLUSION

From this study, soil attenuation profile can be obtained from wavelet analysis with continuous wavelet transform of Morlet wavelet using the data of the surface wave measurement. It is also shown that the characterization of the physical properties of the soil structure in terms of the attenuation coefficient and the shear damping ratio of soft soil layer can be satisfactory obtained using wavelet analysis. In addition, this method has the advantage of being fast, economical and non-destructive.

ACKNOWLEDGEMENTS

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