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COUPLED CWT SPECTROGRAM ANALYSIS AND FILTRATION: NEW APPROACH FOR SURFACE WAVE ANALYSIS
(A CASE STUDY ON SOFT CLAY SITE)

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ABSTRACT

Surface wave analysis consists of generation, measurement and processing of the dispersive Rayleigh waves recorded from two or more vertical transducers. However, in case of soft clay soil, the reliable dispersion curve is difficult to be produced particularly at the frequency below 20 Hz. Some noises from nature and other human-made sources may disturb the generated surface wave data. In this paper, coupled analysis of continuous wavelet transform (CWT) spectrogram analysis based on Gaussian Derivative function was used to analyze the seismic waves in different frequency and time. First analysis is time-frequency wavelet spectrogram which was employed to localize the interested seismic response spectrum of generated surface waves. Second analysis is a time-frequency wavelet filtering approach which was used to remove noisy distortions in the spectrogram. Based on the generated spectrogram, the thresholds for wavelet filtering could be easily obtained. Consequently, the denoised signals of the seismic surface waves were able to be reconstructed by inverse wavelet transform considering the thresholds of the interested spectrum. Results showed that the CWT spectrogram analysis is able to determine and identify reliable surface wave spectrum and phase velocity dispersion curve of soft clay residual soil. This technique can be applied to problems related to non-stationary seismic wave.

INTRODUCTION

The spectral analysis of surface wave (SASW) is one of seismic methods based on the dispersion of Rayleigh waves (R-waves) which is able to determine the shear wave velocity, shear modulus and depth of each layer of the soil profile. The SASW method has been utilized in different applications over the past decade after the advancement and improvement of the well-known steady-state (Jones, 1958) technique. Much of the basis of the theoretical and analytical work of this method for soil investigation has been developed (Stokoe *et al.*, 1994).

Seismic data used in SASW analysis are non-stationary in nature i.e. varying frequency content in time. Especially in the low frequency range measurement, i.e. the soft soil deposit, the interested frequency of surface wave can be relatively low, i.e. it may be less than 20 Hz. In these frequency values, the noisy signals may disturb in the identical frequency level of the surface wave signals generated from the source. Therefore, the time-frequency decomposition of a seismic signal is needed to characterize the correct phase information from signal spectrum. In previous surface wave method, the data analysis in both time and frequency domain has been carried out by fast Fourier transforms (FFT) for various system responses in different frequency from several input motions with time. However, due to Fourier transform works by expressing any arbitrary periodic function of time with period as sum a set of sinusoidal, some information of non-stationary seismic data in analysis maybe lost. The Fourier analysis is unable to preserve the time dependence and describe the evolutionary spectral characteristics of non-stationary processes. Thus, new tools will be required which allow time and frequency localization of the signals 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 transform has been used for numerous studies in geophysics, including tropical convection (Weng & Lau, 1994), the El Niño–Southern Oscillation (Wang & Wang, 1996), the dispersion of ocean waves (Meyers *et al.*, 1993), and wave growth and breaking (Liu, 1994). A complete description of geophysical applications can be found in Foufoula-Georgiou and Kumar (1995), while a theoretical treatment of wavelet analysis is given in Daubechies (1992).

This paper describes the use of a continuous wavelet transform (CWT) to analyze the spectrum of surface waves in different frequency and time domain. This time-frequency wavelet (TFW) spectrum can be employed to localize the interest response spectrum of surface waves on soft soils site. The CWT filtration is also proposed in order to remove the noisy signals from the seismic records which were captured during the field measurement.

CONTINUOUS WAVELET TRANSFORM

The continuous wavelet transform (CWT) technique is an alternative tool for localizing the interested frequency of seismic signal processing particularly in non-stationary problems. Previously, the windowed Fourier transform (WFT) has been used for extracting local-frequency information. The WFT technique is performed on a sliding segment of length from a time series and total length of signal (Torrence & Compo, 1998). Thus, the returned segment can be windowed by an arbitrary function such as boxcar or a Gaussian window (Kaiser, 1994). The WFT analysis is also capable for providing information on time-averaged spectral dynamics which uses a sinusoidal wave with a finite energy symmetric window. In addition, the WFT has a constant time frequency resolution. This resolution can be changed by rescaling the window. However it is not well suited for characterizing the instantaneous behaviour of seismic signal because WFT only produces the time and frequency spreads of constant Fourier functions. The seismic signals contain many transient events produced from waveform change when the seismic waves propagate in layered medium. The seismic signals are also locally non-stationary in both time and Fourier-space. Thus, the wavelet transformation is needed due to the fact that the wavelet decomposition utilizes a localized waveform as the basis function. A presentation of basic wavelet theory may be found in literatures such as Daubechies (1992), Farge (1992), Kaiser (1994).

Wavelets dilate in such a way that the time support changes for different frequency. When the time support increases or decreases, the frequency support of the wavelet is shifted toward high or low frequencies, respectively. Therefore, as the frequency resolution increases, the time resolution decreases and vice versa (Mallat, 1989). This optimal time-frequency resolution property makes the CWT technique useful for non-stationary seismic 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 $\psi(t)$, it can be used to produce a family of wavelets 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 $\sigma \neq 0$)

Unlike Fourier transform, the wavelet has various wavelet shape used for signal analysis which is called the mother of wavelet. The choice of appropriate wavelet shape used in signal analysis depends on the seismic waveforms. The family of wavelets can be divided into two groups (Soman and Ramachandran, 2005) i.e. continuous wavelet transform (CWT) and discrete wavelets transform (DWT). Some mother wavelets which are commonly used in the CWT are Gaussian, Morlet, Paul and Mexican Hat. 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:

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

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

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

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

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

In this study, the mother wavelet of the Gaussian Derivative was used. The real component of the Gaussian Derivative wavelet in the time and frequency domains is defined as follows:

$$\psi_0(t) = \frac{(-1)^{m+1}}{\sqrt{\Gamma\left(m+\frac{1}{2}\right)}}\frac{d^m}{d\eta^m}\left(e^{-t^2/2}\right) \tag{5}$$

$$\hat{\psi}_0(s\omega) = -\frac{i^m}{\sqrt{\Gamma\left(m+\frac{1}{2}\right)}}(s\omega)^m\left(e^{-(s\omega)^2/2}\right) \tag{6}$$

where *m* is the wave number and Γ is the Gamma function. The complex wavelet is generated by the addition of a Heaviside function in the frequency domain. This wavelet decays with the square root of the gamma function. The Gaussian Derivative has wavelet's derivative order that can be varied in order to get the best resolution of the waveform. The derivative order of 2 in the Gaussian Derivative is known as the Marr or Mexican Hat wavelet while at its derivative order of 80, the Gaussian Derivative wavelet contains about the same oscillation count as the Morlet with a wavenumber of 12. The Gaussian Derivative wavelet's frequency domain representation is exactly a gamma peak shape. The right shifted skew of the frequency peak is appreciably less than that of the Paul wavelet, and higher values for the derivative of the Gaussian Derivative wavelet produce nearly Gaussian frequency peaks.

In the time and frequency domain, the plot of Gaussian Derivative wavelet is shown in Fig.1 and 2. In Fig.1, the complex Gaussian Derivative wavelet is shown within an adjustable parameter *m* of 27 which is used in this study. This parameter can be used for an accurate signal reconstruction of low frequency seismic surface waves. The Gaussian's second order exponential decay used in time resolution plot results in very good time localization.

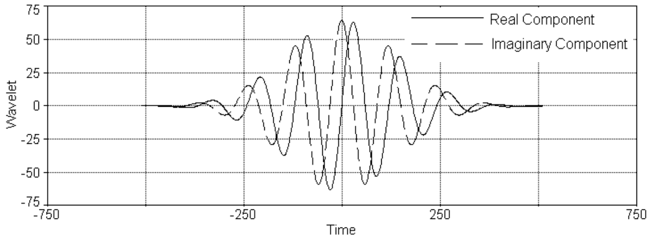


Fig. 1 Time domain plot in complex function of Gaussian Derivative wavelet

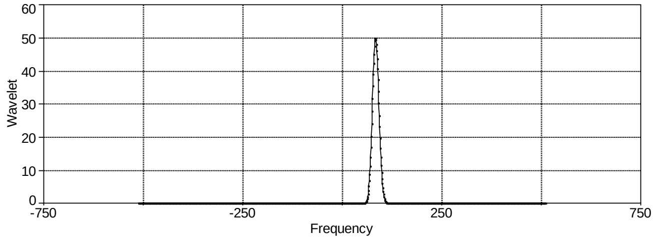


Fig. 2 Frequency domain plot in complex function of Gaussian Derivative wavelet

RESEARCH METHOD

SASW Measurement Setup

Three key elements of surface wave analysis on SASW method are measurement of seismic wave energy at suitable distances from impact sources, developing the experimental dispersion curve and performing the inversion analysis for the shear wave velocity profile. In this study, SASW method was employed to collect the seismic surface wave propagation data in soft soil site. A set of impact hammer sources of various frequencies were used to generate R waves on the soil surface. The propagation of the waves were detected using two receiving geophones and the analog signals were then transmitted to a spectrum analyzer which consisted of acquisition box and transferred digitally to a notebook computer (Fig. 3).

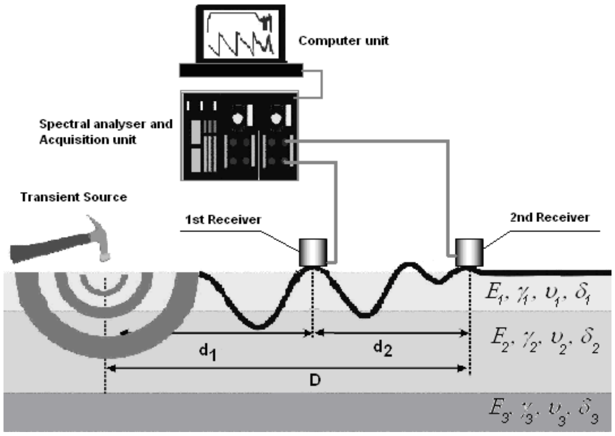


Fig. 3. SASW measurement setup applied on the sites

The sledge hammers of 3 and 8 kg were used as a transient impact source in the SASW measurement. A transient source allows a test to be performed relatively quickly because a broad range of frequencies is generated and measured simultaneously. However, the frequency content is often limited and it is also important to realize that different transient sources generate energy over different frequency ranges. Prior to the experiments, a pilot study on frequency range test on transient hammers used in this study was carried out. Both hammers generated surface waves over different frequency range with adequate amplitude and they can be detected by the receivers. For a typical soil deposit, the highest frequency necessary is in the order of 200 to 800 Hz (Nazarian, 1984). Therefore, both hammers are appropriate to be used for sampling the soil layer.

Vertical geophone of 1 Hz was used in this study. The geophone only receives the vertical displacement component of the generated signal from the impact sources which is the only interested component in the SASW measurement. Several configurations of the receiver and the source spacings were required in order to sample different depths. The measurement configuration of the SASW test used in this study is the mid point receiver spacings. In addition, the short receiver spacings with a high frequency source were used to sample the shallow layers of the soil profile. Larger receiver spacings with a set of low frequency sources were employed to sample the deeper layers. The distance between the source and the near receiver was set up equal to the distance between the receivers (Fig. 3). This configuration is adequate for reducing the near-field effect (Heisey *et al.*, 1982; Ganji *et al.*, 1998).

Conventionally, all the signals collected from the recorder were directly transformed using the fast Fourier Transform (FFT) to frequency domain with limited filtering techniques employed. Previously in SASW method, the coherent signal averaging is used to reduce the random noise level or to eliminate incoherent signals. The coherent technique usually is used as a guide to make judgments on the quality of the signals collected but it does not always provide a clear guidance of the frequency event of true surface wave signals. The most important spectrum function in the frequency domain in SASW measurement is the phase information of the transfer function. The transfer function spectrum was used to obtain the relative phase shift between the two signals in the range of the frequencies being generated.

A composite experimental dispersion curve from all receiver spacings in one configuration measurement was generated through unwrapping the data of the phase angle from the transfer function and phase velocity calculated using the phase difference method. Eventually, the actual shear wave velocity of the soil profile was then produced from the inversion of the composite experimental dispersion curve.

In the inversion process, each layer of the soil profile was assumed as a homogeneous layer extending to infinity in the horizontal direction. A theoretical dispersion curve was then calculated based on the initial profile using several wave propagation theories. The theoretical dispersion curve was ultimately matched to the experimental dispersion curve of the lowest root-mean-square (RMS) error with an optimization technique. Finally, the profile with the best-fitted (representing the lowest value of RMS) of the theoretical dispersion curve to the experimental dispersion curve was used to represent the most likely profile of the site.

Test Site Location and Soil Investigation

Location of the test site location at RTM, Kelang is shown in Figure 4. The site is in the vicinity at the existing RTM antenna tower open field. The site is a fairly flat open padi field and on going construction was seen about 500 m away from the site. The site is generally an original ground and the soil mass is mainly of greyish clay. The regional geology of the site has been classified as recent quartenary of dominantly alluvial deposits of soft marine clay with traces of organics.

Drillings and samplings were carried out using multi-speed rotary wash boring using water as the flushing medium. HW casings of 100 mm diameter were used to prevent the collapse of the borehole wall. The undisturbed sample was obtained using thin walled stationary piston sampler in compliance to BS5930:1981. Three boreholes were drilled down to depths of 15 m for the purpose sampling. The soil descriptions from the three boreholes have shown that the soil type found were quite similar, i.e. greyish clay with decayed wood at most of the soil layers of the subsoil stratum. The subsoil profiles from the three boreholes are summarized as shown in Figure 5.

Fig. 4. SASW measurement setup applied on the sites

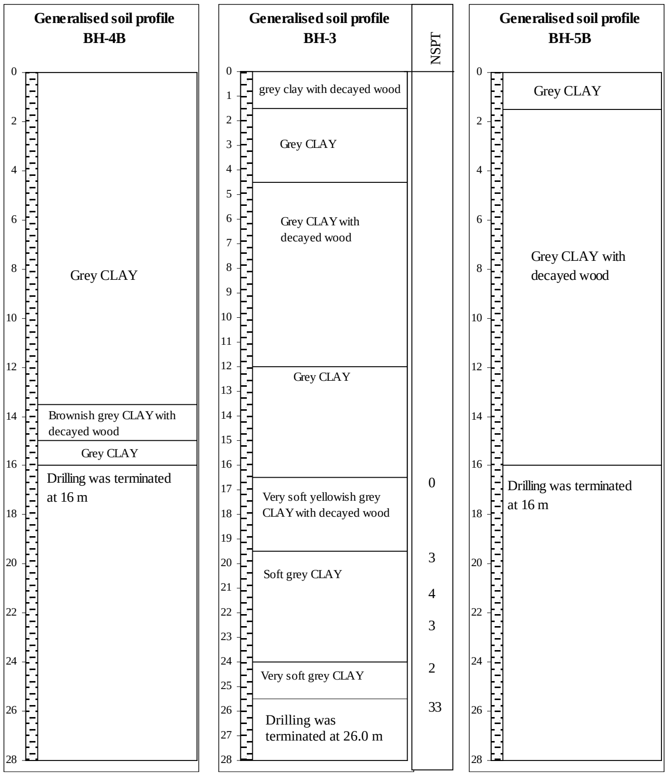


Fig 5. Summary of subsoil profile from three boreholes

Cone penetration test is an in situ test that is used to evaluate the geotechnical subsoil properties in term of in situ shear strength and compressibility. This is done by pushing a sensor that could measure continuously and simultaneously the tip resistance, sleeve friction and the pore water pressures at a required depth. Using these measured parameters, the geotechnical engineer is able to interprete the geotechnical condition of the subsoil wich will be considered in the design of foundation. The electrical type of cone penetration instrument (CPTU), which is also known as piezocone, was used in this project together with a 200 kN hydraulic jacking system.

CPTU were carried out at three nearby boreholes locations. The tests were conducted continuously starting from the ground level down to 25 m depth. The measured cone point resistance (q_c), sleeve friction (f_s), in situ pore pressure (u_o), dynamic pore pressure (u) and friction ratio (Rf) were recorded at every 0.2 m depth intervals. Dissipation tests were also carried out for each CPTU at selected locations of 1.5, 3.0, 4.5, 6.0, 9.0, and 12.0 m depths. An example of CPTU test result is shown in Figure 6.

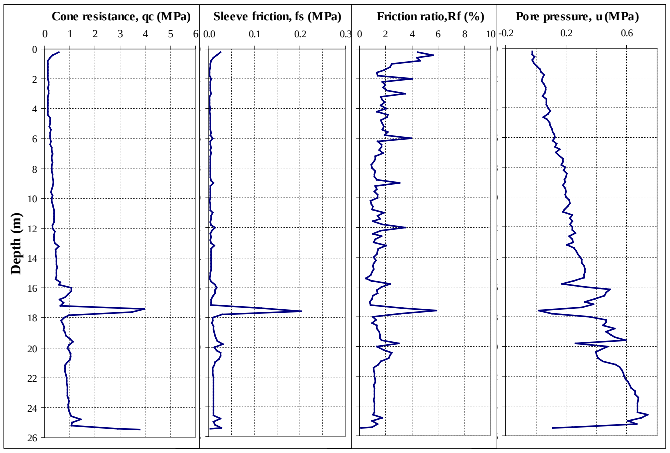


Fig 6. Profile of CPTU result

Laboratory tests were carried out to determine the physical and mechanical properties of the subsoil foundation at the test site. Bulk density of the subsoil at the test site ranges from 12.63 to 21.19kN/m^3 (average of 14.22kN/m^3). The specific gravity values ranges from 2.45 to 2.60. Based on the USCS system, the soil was classified as clay-silt with high plasticity and symbolized with CH-MH.

Using soil classification chart based on normalized CPT and CPTU data (Robertson, 1990), CPTU data can be classified as clay to silty clay and silty clay to clayey silt (Figure 7). From the evaluation of undrained shear strength, s_u, based on CPT data the subsoil at the test site can be divided into 3 layers, i.e. very soft clay with *su* of 8.50 kPa (0.0 – 5.7 m), soft clay with *su* of 20.00 kPa (5.7 – 12.0 m) and medium clay with *su* of 32.85 kPa (12.0 – 16.0 m).

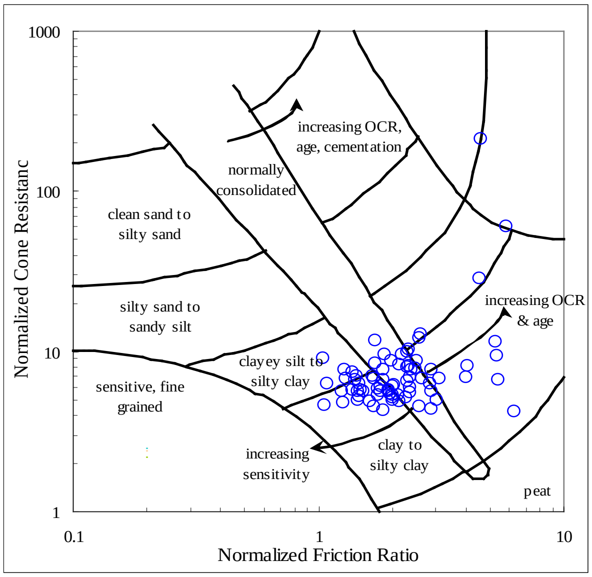


Fig 7. Profile of CPTU result

Procedure of CWT Spectrogram Analysis and Filtration

The proposed procedures to analyze CWT spectrogram and filtration comprise of the following steps:

1. Chose the wavelet function and a set of scale, *s*, to use in the wavelet transform. The different wavelets may influence the time and frequency resolution.

2. Develop the wavelet scalogram by implementing the wavelet transform (Eq.2) using computing a convolution of the seismic trace with a scaled wavelet dictionary. Wavelet scale is calculated as fractional power of 2 using the formulation:

$$s_j = s_0 2^{j\delta_j}, j = 0, 1, ..., J \tag{7}$$

$$J = \delta j^{-1} \log_2 \left(\frac{N\delta_t}{s_0} \right) \tag{8}$$

where,

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

3. Convert the scale dependent wavelet energy spectrum (scalogram) 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 is developed base on the simple truncation filter concept which only considers the passband and stopband.

Figure 8 shows the scheme of the proposed CWT filtration for time and frequency domain in the CWT spectrogram. Threshold values in time and frequency domain are as 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 signal can be eliminated by zeroing the spectrum energy and they are fully removed when reconstructing the time domain signal. Thus, the interested spectrum of signals can be passed when the spectrum energy is not set as 0 or it is maintained in original value. Design of the CWT filtration can be written as:

$$f(s) = \begin{cases} 0, & 1 \le s \le F_l \\ 1, & F_l \le s \le F_h \\ 0, & F_h \le s \le N \end{cases} \qquad (9)$$

$$f(u) = \begin{cases} 0, & 1 \le u \le T_l \\ 1, & T_l \le u \le T_h \\ 0, & T_h \le u \le N \end{cases} \qquad (10)$$

The value of 1 means the spectrum energy is passed and the value of 0 represents as the filtration criteria when the spectrum energy is set as 0.

5. Reconstruct the time series of seismic trace using Eq.3

6. Calculate the phase different from reconstructed signals at each frequency to develop the phase spectrum for the experimental dispersion curve. The phase data can be calculated from:

$$\phi_n(s) = \arctan\left(\frac{\Im\left\{s^{-1}W_n^{XY}(s)\right\}}{\Re\left\{s^{-1}W_n^{XY}(s)\right\}}\right) \qquad (11)$$

where,

$W_n^{XY}(s) = W_n^{X}(s) W_n^{Y*}(s)$ = wavelet cross spectrum

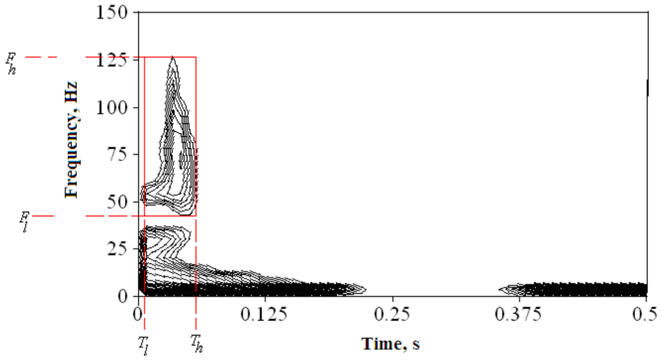


Fig 8. CWT filtration scheme

RESULTS AND DISCUSSION

Signal Analysis using FFT

Figure 9 shows the recorded signals from impact source. The vertical transducer (channel) 1 and 2 were located at the distance of 8 m and 16 m from the source, respectively. The waveform of seismic signal recorded (Fig.9) is transient and-non stationary.

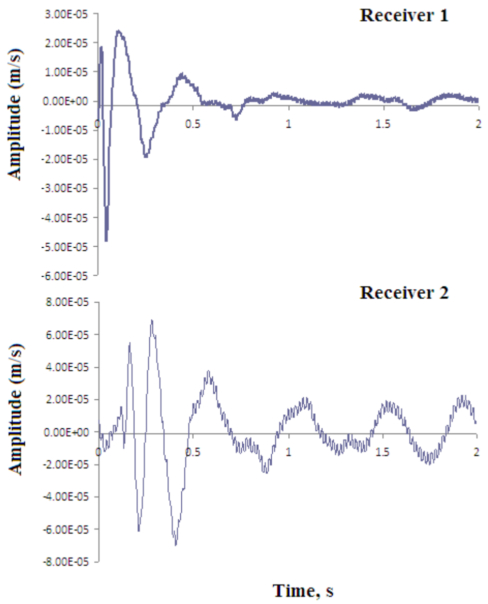


Fig 9. Surface wave signals recorded from two receivers

Weak recorded signal of seismic wave was found in both receivers. It can be identified as an effect of environmental noise which maybe produced from ground noise and man-made vibrations. These noises are also termed as coherent noise (i.e. ground roll, surface reflections and reflected refractions). The coherent noise energy can be distinguished from the incoherent noise or random noise (i.e. wind shaking the geophones) in different frequency event. The coherent noise is low frequency due to the earth filtering whereas random noise is high frequency due to the short radiation path in the near surface (Li and Tang 2005). Noise event plays a crucial roll in statistical analysis of seismic data. Seismic processing is strongly dependent on the quality of the recorded signals. The interference of noise in seismic data also causes non-identical input signals or behaviour of system at different periods.

(6.17)

Using the fast Fourier transform (FFT) analysis, both signals were transformed to the Fourier amplitude spectrum in the frequency domain (Fig.10). The Fourier spectrum from recorded signals shows several peaks of energy event with different frequency band. These spectrums can be used to identify the dominant frequency of the signal system. The first event may be identified as the dominant low frequency peak which could be produced from high energy ground noise. The second event is the seismic signals of interest in this measurement. However, this seismic event cannot be well identified in the spectrum due to low frequency noise event which strongly disturbed the recorded signal. The noise event seems more stationary and appears in the form of various frequency bands and has the greatest energy at lower frequency than the seismic event. The third event comes from the higher frequency background noise (electrical noise) which is also known as the coherent noise (Li & Tang, 2005). However, it is still quite difficult to interpret the frequency band of interest of the seismic signal.

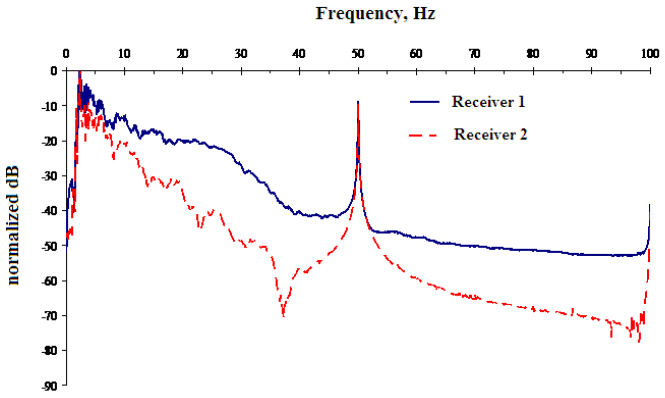
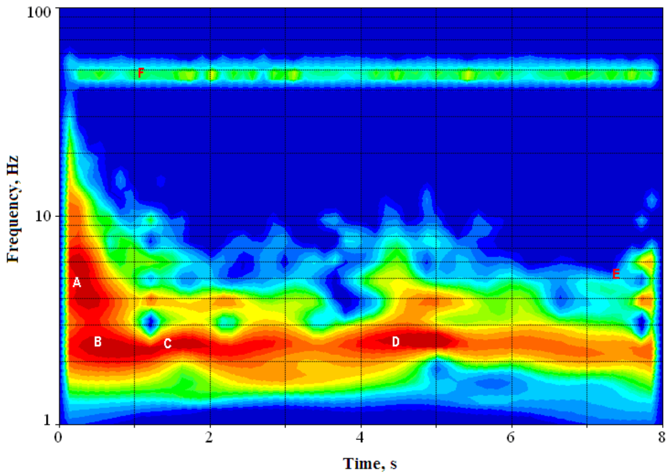


Fig 10. Amplitude/power spectrum of surface wave signals

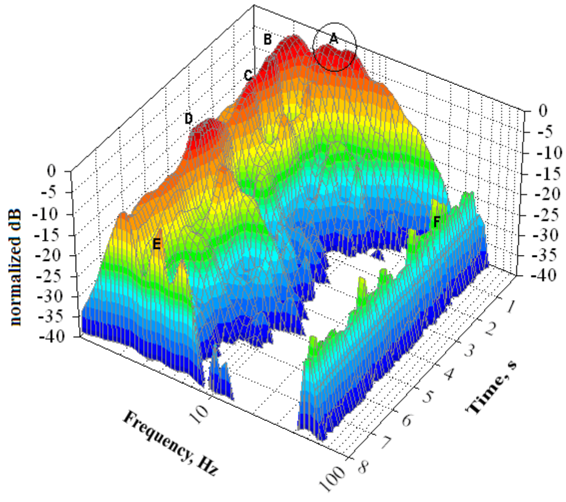
In addition, when the signals were transformed into frequency domain, time-dependent behaviour of the seismic waves and noisy events were also lost. The energy content of these events which are present at different times and frequency would not be picked up by conventional Fourier analysis. In other words, the conventional spectral analysis of non-stationary signal of seismic waves cannot describe the local transient event due to averaging of the signals. It also cannot instantly separate the event of true seismic waves from noisy signals. Consequently, it is difficult to capture the correct phase information in the transfer function of both signals. An approach to overcome these difficulties is presented in the following section.

CWT Time-Frequency Analysis and Signal Reconstruction

The time-frequency (TF) analysis of CWT was then employed to overcome the identification problem of spectral characteristics of non-stationary seismic wave signals. The typical CWT spectrogram for seismic signals (Fig.9) with an improved time-frequency resolution is shown in Fig.11 and Fig.12 for signals received at receiver 1 and 2, respectively. The TF decomposition of CWT was carried out by a mother wavelet of Gaussian Derivative (Fig.1). The CWT of Gaussian Derivative wavelet provides good resolution at low frequency and is effective in the detection of low frequency noises using the various derivation orders. From Fig.11 and Fig.12, three main energy events at different frequency bands were clearly detected which may result in both low and high mode of seismic and noisy signals. It can be seen that low frequency energy was found in the range of up to 2 - 3 Hz in both CWT spectrograms. This spectrum range is identified as noisy signals or ground roll (B, C, D, E group). The level and frequency range of the noisy signals were determined by independent-measurement of noise background. The measurement was conducted by putting the geophones on the ground at 8 m spacing and the signal gain was measured at high level. Thus, the threshold sensitivity for both receivers were set up to the low level where the dominant noisy signals at this frequency range can be clearly captured.



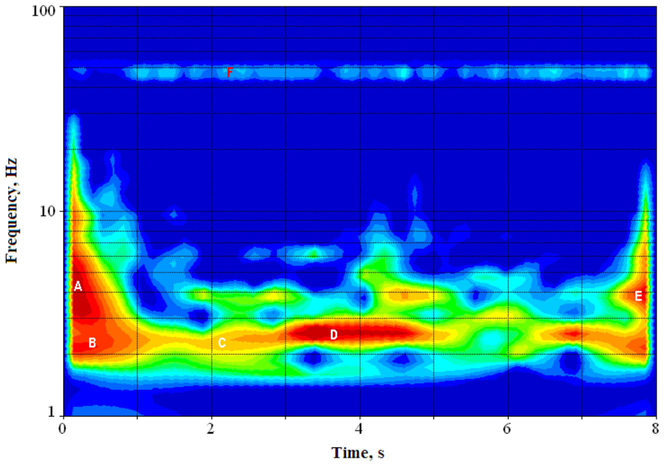
(a) 2-D CWT Spectrogram



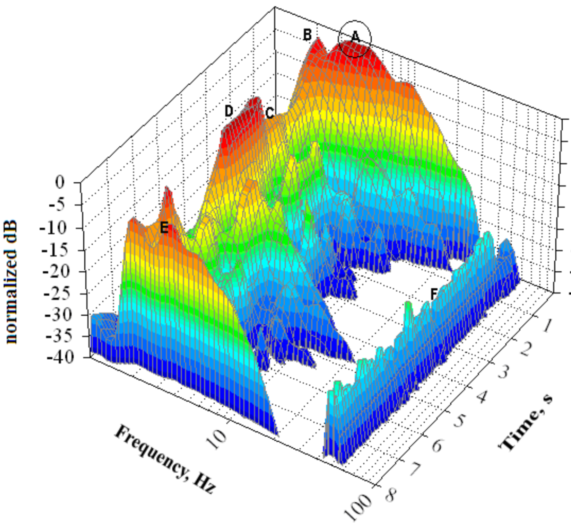
(b) 3-D CWT Spectrogram

Fig 11. CWT Spectrogram for Received Signal 1

From Fig.12 and 13, in addition to noisy signals, two other peak events were clearly detected. The first event is in the range of 50 Hz (F group) which was recognized as the electrical signal. The second event (A group) is the spectrum range of the seismic waves of interest. It was found in range of 3 to 7 Hz for signals recorded on receiver 1 and 2. As discussed above, the presence of noise in the measured seismic signals tend to reduce the clarity of the phase information from the transfer function. Denoising and cleaning noisy signals is possible in order to improve the clarity of response spectrum analysis. A simple approach to remove noisy distortions in the spectrogram is to use the wavelet filtering.



(a) 2-D CWT Spectrogram



(b) 3-D CWT Spectrogram

Fig 11. CWT Spectrogram for Received Signal 1

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, time and frequency range of noisy signals was set as threshold of wavelet filtering (Eq. 9 & 10). It means that the noisy signals are removed from the spectrogram and only the interested seismic wave signals remain. The values of time and frequency threshold are described in Table 1. The second is that the inverse wavelet transform then returns a denoised seismic signal. Fig.12 demonstrates the application of the Gaussian Derivative wavelet in denoising and reconstructing the recorded seismic signals in Fig.9. Fig.13 shows the phase spectrum from denoised signals from the SASW measurement. Compared to the phase spectrum from original signals, the enhanced phase spectrum from the CWT filtration provides the better phase information versus frequency range without noisy interference needed in the SASW analysis. Both figures show that the CWT and wavelet filtering is an effective tool for identifying, denoising and reconstructing the noisy seismic surface waves measured on the soil profile.

Table 1. Threshold value in time and frequency domain

Signal	T_l	T_h	F_l	F_h
Receiver 1	0.030	0.653	2.970	7.079
Receiver 2	0.002	0.441	2.752	6.028

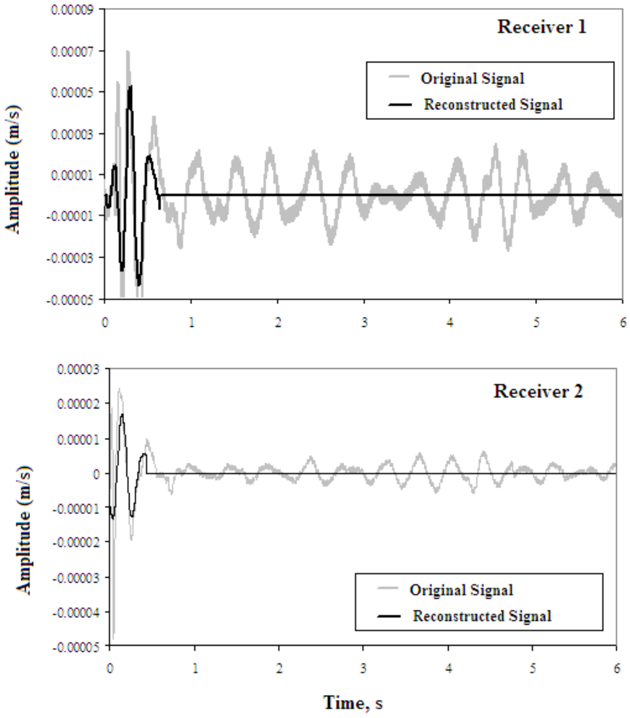


Fig. 12 Reconstructed signals from the CWT filtration

<u>Dispersion Curve from CWT Analysis</u>

Figure 14 presents the experimental dispersion curve from 8 m receiver spacing. The dispersion curve is constructed based on the phase spectrum of reconstructed signals (Fig. 13) from the CWT filtration.

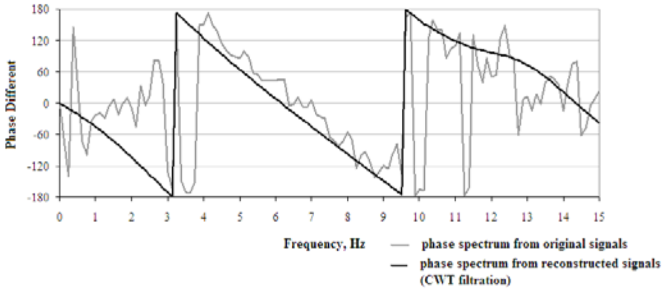


Fig. 13 Comparison between enhanced phase spectrum from CWT filtration and original signals

To verity the CWT filtration technique for interpretation of the phase spectrum, the impulse response filtration (IRF) technique proposed by Joh (1996) was implemented. Using the same seismic data, the experimental dispersion curve calculated from enhanced phase spectrum based on the IRF analysis was generated as shown in Figure 14. The dispersion curve determined from the CWT filtration technique is almost the same as the one obtained by IRF technique. This indicates that the signal filtration by CWT analysis is practically applicable to the construction of an experimental dispersion curve in the SASW measurement.

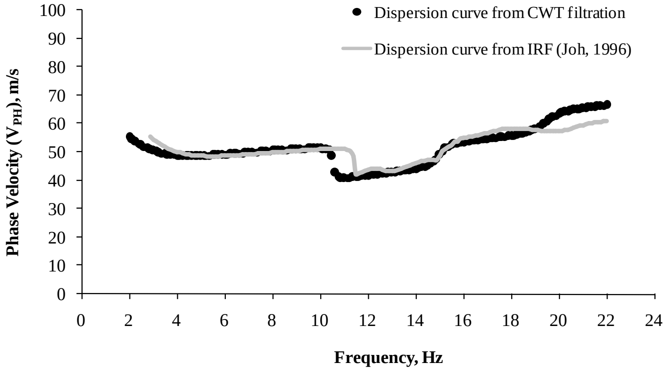


Fig. 14 Comparison of dispersion curve between the CWT filtration and IRF technique (Joh, 1996)

The dispersion curve from CWT analysis is also validated by the CSW measurement which was carried out in the same location of the SASW measurement. The CSW method is the surface wave measurement which is performed by a controlled frequency source of harmonic vibration. A set of frequency generated from harmonic vibration source was set up in the range of 5 until 20 Hz. Figure 15 shows the comparison of dispersion curve determined by the CSW method and the phase spectrum from the CWT filtration. This comparison presents that the original phase spectrum interpreted by the CWT filtration technique is in perfect agreement with the dispersion curve determined by the CSW method.

CONCLUSION

In this paper, the identification, denoising and reconstruction of the wave response spectrum from seismic surface wave propagation on a residual soil using time-frequency analysis of continuous wavelet transforms was presented. The mother wavelet of Gaussian Derivative was used for providing good resolution of spectrogram at low frequency and is also effective in the detection of low frequency noises. The spectrogram could be used to clearly identify the various events of interest of the seismic surface waves and noisy signals.

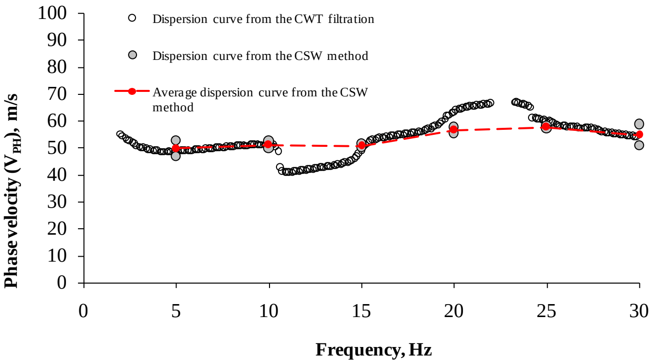


Fig. 15 Comparison of dispersion curve between the CWT filtration and the CSW method

Base on the generated spectrogram, the thresholds for CWT filtration could be easily obtained. Consequently, the denoised signals of the seismic surface waves were able to be reconstructed by inverse wavelet transform considering the thresholds of the interested spectrum. Finally, the CWT based on Gaussian Derivative wavelet is a potential tool and useful in spectral analysis, time-frequency decomposition for the identification of transient events in non-stationary signal and filtering of noisy signals in seismic surface waves records.

A good agreement was obtained between the dispersion curve obtained from the phase spectrum based on the CWT filtration compared to the dispersion curve analyzed from the IRF technique and the experimental dispersion curve from the CSW measurement.

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