Wavelet-Spectrogram Analysis of Surface NDT Pavement

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Wavelet-Spectrogram Analysis of Surface Wave Technique for Quick NDT Measurement on Surface Layer of Pavement

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Abstract. Reliable assessment of in situ pavements stiffness is an important aspect in effectively managing a pavement system. The aim of this paper is to propose the new procedure, namely the wavelet-spectrogram of surface wave (WSSW) technique for non-destructively measurement of elastic modulus on surface layer of a pavement system. Using two receivers, surface wave propagation on pavement surface was recorded and transformed into in frequency domain by wavelet analysis. For this analysis, a derivative Gaussian wavelet was selected as an appropriate mother wavelet for seismic waveform propagating along pavement surface. Thus, an interactive 2-D plot of time-frequency spectrogram consisting of wave-energy spectrum was simultaneously generated. CWT-filtration method was implemented in order to reduce the effect of noisy signal recorded during measurement. From selected wave spectrogram, the unwrapped phase different spectrum was generated to obtain phase velocity which was performed by least-square linear regression. Finally, the elastic modulus of pavement surface layer was calculated from a modified relationship between phase velocity, Poisson ratio and density of pavement surface layer. The results show that the proposed technique is able to measure in situ elastic stiffness of the surface layer. In addition, the change of the surface layer stiffness is also able to be monitored. The stiffness (elastic modulus) produced by the WSSW technique is classified as a modulus at very low strain level.

1 Introduction

The spectral-analysis-of-surface-wave (SASW) is a well-known of non-destructive techniques (NDT) in pavement evaluation and geotechnical investigation. The SASW employs the surface waves dispersion in order to determine the shear wave velocity corresponding to stiffness of each layer at pavement and soil profile. The method performs three steps of an elaborated data process, i.e., (1) collecting seismic data, (2) constructing an experimental dispersion curve and (3) conducting an inversion process of the dispersion curve for generating a stiffness profile. The method has been improved and utilized in many civil engineering applications, e.g., site characterization (Stokoe et al. 1994), soil density (Kim et al. 2001), pavement characterization (Rosyidi et al. 2007, Yusoff et al. 2015), soil damping measurement in soft soil sites (Rosyidi and Taha 2012), and asphaltic pavement measurement (Hazra and Kumar 2014, Rosyidi 2015).

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In inversion process, the advanced mathematical approach is required to produce the stiffness profile from a dispersion curve. Reliable inversion procedure using stress-wave propagation theories, i.e., the transfer matrix method, the dynamic stiffness matrix method and the finite difference method should be employed. All the methods require an initial profile model consists of a set of homogeneous layers extending to infinity in the horizontal direction. In each layer of profile, the information such as a thickness, a shear wave velocity, a Poisson's ratio (or compression wave velocity), and a mass density are assigned. Based on the initial profile, a theoretical dispersion curve is calculated using one of these wave propagation theories. The theoretical dispersion curve is then compared with the experimental dispersion curve. If the two dispersion curves do not match, the initial profile (number of layers, layer thickness, shear wave velocity, or any combination) is adjusted, and another theoretical dispersion curve is calculated. The trial-and-error procedure is repeated until the two curves match, and then the associated assumed profile is considered the real profile. In addition, when the SASW method is performed on irregular stiffness profile, i.e., pavement structure, the trial-and-error procedure becomes a difficult analysis and takes longer time in data processing. Moreover, several researchers have reported on difficulties related to surface wave measurements at pavement sites. Most of these difficulties are reported to originate from the influence of higher modes of propagation (Al-Hunaidi 1992, Tokimatsu et al. 1992, Ganji et al. 1998; Ryden et al. 2004).

The seismic surface wave method is not able to separate different modes of propagation on a pavement system and thus measures a superposition of all propagating waves at the specific receiver locations. This superposed effect, often termed apparent phase velocity or pseudophase velocity, changes with distance and has forced the evaluation of the data to take into account the position of the receivers and the superposition of different modes for the inversion of experimental dispersion curves. Ryden et al. (2004) proposed a new approach in seismic pavement testing where the different modes of propagation are separated, thereby potentially clarifying some of the noted difficulties with the SASW method applied to pavement testing. Their approach is based on the multichannel analysis of surface wave (MASW) data processing technique. However, due to complexity in surface wave analysis, application of these methods on pavement evaluation is still relatively limited. On the other hand, in pavement evaluation system, the need of accurate, cost-effective and non-destructive evaluation is becoming ever important because the rehabilitation and management of roads is becoming increasingly difficult due to the increasing number of aging roads and limited budgets. As well, for practical purpose, pavement engineer usually needs a quick and relatively effortless analysis for determining the structural condition of pavement surface layers.

In this paper, a new procedure in a surface wave technique which is using continuous wavelet transform combined with the elastic stiffness formulation for obtaining the phase velocity is introduced. This method is namely the wavelet-spectrogram of surface wave (WSSW) technique. The time-frequency decomposition of continuous wavelet transform (CWT) on seismic signals is employed to characterize the phase information of phase different spectrum. It provides a reliable information of wave spectrum in the pavement profile. An algorithm on phase different calculation in this analysis aims to avoid the use of a complex inversion algorithm to obtain the elastic modulus of the pavement surface layer. In the SASW method, data analysis and processing in frequency domain has been carried out by fast Fourier transforms (FFT). However, due to Fourier transform works by expressing any arbitrary periodic function of time with period as sum a set of sinusoidal, this analysis becomes inconsistent and is unable to preserve the time dependence and describe the evolutionary spectral characteristics of non-stationary processes (Rosyidi et al. 2009). Wavelet analysis is becoming an effective 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. A typical result from a case study is presented herein for the structural assessment of an existing asphalt concrete (AC) pavement in Purwakarta, West Java, Indonesia.

1.1 Continuous Wavelet Transform

The continuous wavelet transform (CWT) has been used in many studies in geophysics (Foufoula-Georgiou and Kumar 1995) and civil engineering application (Rosyidi et al. 2009). The continuous wavelet transform (CWT) technique is an alternative tool for localizing the interested frequency of seismic signal processing particularly in non-stationary problems. 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. The characteristic of time-frequency resolution creates 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:

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

where σ is the dilation parameter or scale and τ is the translation parameter ($\sigma, \tau \in \Re$ and $\sigma \neq 0$). The wavelet has also various wavelet shape used for signal analysis which is called the mother of wavelet, i.e., Gaussian, Morlet, Paul and Mexican Hat. An appropriate selection of wavelet shape signal analysis depends on the seismic waveforms.

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:

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

where $\bar{\psi}$ is the complex conjugate of ψ, $F_W(\sigma,\tau)$ is the time-scale map.

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

$$\psi_0(t) = \frac{(-1)^{m+1}}{\sqrt{\Gamma\left(m+\frac{1}{2}\right)}} \frac{d^m}{d\eta^m}\left(e^{-t^2/2}\right) \tag{3}$$

$$\hat{\psi}_0(s\omega) = -\frac{i^m}{\sqrt{\Gamma\left(m+\frac{1}{2}\right)}}(s\omega)^m\left(e^{-(s\omega)^2/2}\right) \tag{4}$$

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 GoD has wavelet's derivative order that can be varied in order to get the best resolution of the waveform.

2 Research Method

2.1 Field Measurement

In field measurement of the WSSW method, a set of ball bearing with weight from 5 to 15 g was used as an impact source to generate seismic waves on the surface layer of pavement. Generated seismic waves were then detected using two high frequency accelerometers. Consequently, the signals were recorded using an ADT analog-digital acquisition connected to a notebook computer for post processing (Fig. 1). In this study, two configurations of mid-point receiver spacing and the receiver-source spacings were employed in order to sample different depths of pavement surface. The configuration of mid-point receiver spacings was described in Fig. 2. The receiver spacing (d_2) was obtained as a distance which the length is less than and/or equal to the thickness (H) of pavement surface layer. Whereas, the distance between a source and first receiver (d_1) was set as equal to receivers spacing (d_2). Due to the interested pavement area in measurement was asphaltic surface layer, the short receiver spacings of 5, 10 and 15 cm with a high frequency source were only used. In the test, repetition procedure (forward and backward) until at least 4 to 6 times in each receiver spacing measurement should be employed in order to minimize the effect of internal phase shift between receivers and to enhance a good average of received signals.

Beside the WSSW test, the SASW measurement was also carried out at same sites of existing road pavement in Purwakarta, West Java, Indonesia. The pit test was also conducted to acquire the information of a pavement profile. From the pit test, the pavement structure consists of an asphalt concrete (AC) layer (18 cm), crushed stone of base course (10 cm), sub-base course (30 cm) over a subgrade layer.

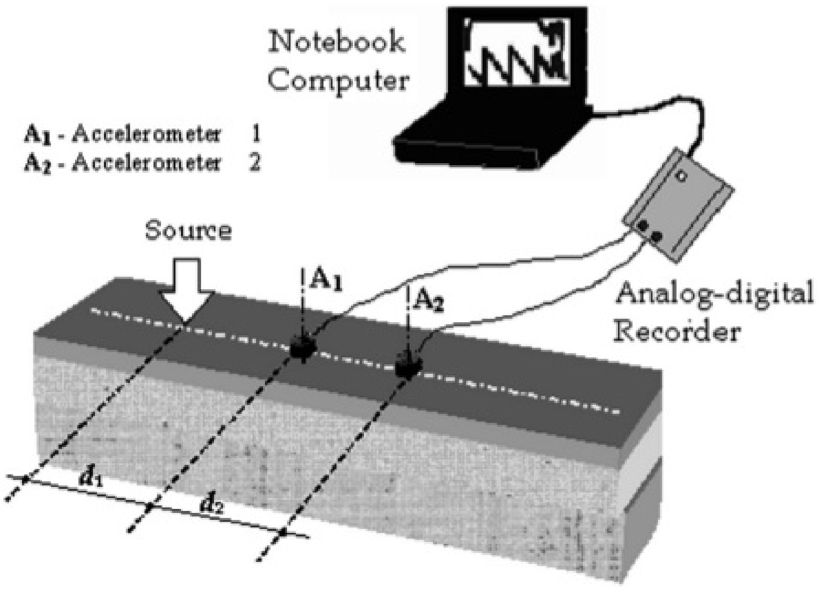


Fig. 1. Experimental set up of WSSW measurement on a pavement structure

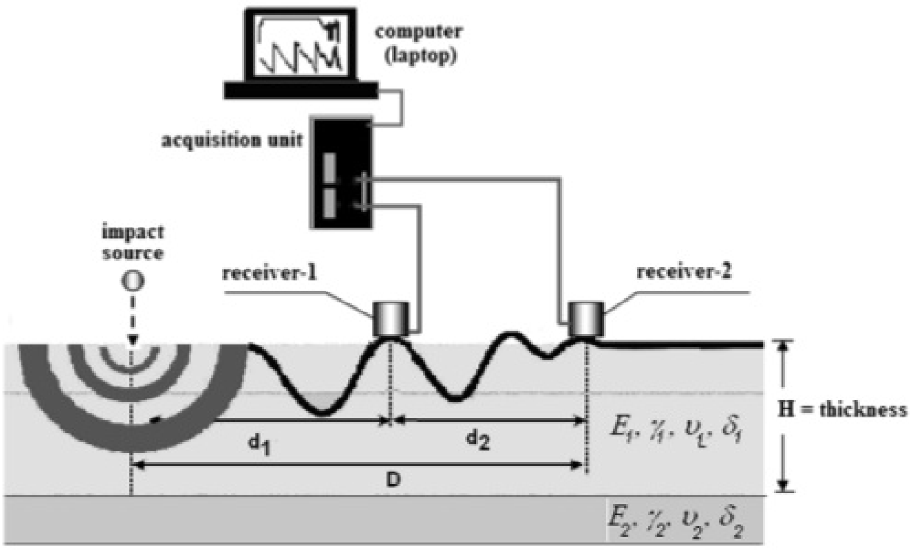


Fig. 2. Mid-point receivers configuration of WSSW measurement on pavement structure

2.2 Data Analysis and Process

A proposed procedure of the WSSW method consists of seismic data analysis using continuous wavelet transform and elastic modulus calculation of elastic linear model on pavement surface layer which is described as follows:

1. The seismic wave data are collected from field measurement using a configuration of the mid-point receiver spacings.
2. The time-frequency spectrum analysis based on continuous wavelet transform of Gaussian Derivative (DoG) mother wavelet is carried out for two signal waveforms recorded from field measurement. By decomposing a time series of seismic

waveform into time-frequency (TF) spectrogram, the dominant modes of variability and how those modes vary in time can be determined very well.

3. Phase information of the transfer function (phase spectrum) are then determined from both TF spectrograms. The data informs the time difference of wave propagating from first to second receiver. A mathematical expression for calculating phase spectrum from TF spectrogram is defined by (Rosyidi and Taha 2012):

$$H(f) = \frac{Y(f)}{X(f)} \approx \frac{W^{Y}_{f(u,s)}}{W^{X}_{f(u,s)}} = \frac{\int\limits_{-\infty}^{\infty} Y(t)\,\frac{1}{\sqrt{\sigma}}\psi * \left(\frac{t-\tau}{\sigma}\right) dt}{\int\limits_{-\infty}^{\infty} X(t)\,\frac{1}{\sqrt{\sigma}}\psi * \left(\frac{t-\tau}{\sigma}\right) dt} \tag{5}$$

where,

$X(f)$ = spectrum input of signal, $X(t)$, from first receiver,
$Y(f)$ = spectrum output of signal, $Y(t)$, from second receiver,

$$W^{Y}_{f(u,s)} = \int\limits_{-\infty}^{\infty} Y(t)\,\frac{1}{\sqrt{s}} g\left(\frac{t-u}{s}\right) e^{-i\xi(t-u)} \tag{6}$$

$$W^{X}_{f(u,s)} = \int\limits_{-\infty}^{\infty} X(t)\,\frac{1}{\sqrt{s}} g\left(\frac{t-u}{s}\right) e^{-i\xi(t-u)} \tag{7}$$

From Eq. 7, the phase spectrogram in time-frequency domain can be obtained by:

$$H(u,s) = \frac{W_f^{XY}(u,s)}{W_f^{XX}(u,s)} = \frac{\left|W_f^{XY}(u,s)\right| e^{i(\theta_Y(a,b)-\theta_X(a,b))}}{W_f^{X}(u,s)^{*} \times W_f^{X}(u,s)} \tag{8}$$

Thus, phase different is obtained from the ratio of the imaginary to real part of the phase spectrogram which is expressed as:

$$\phi = \tan^{-1}\left(\frac{\Im\, H(u,s)}{\Re\, H(u,s)}\right) \tag{9}$$

4. The coherence function is used to visually inspect the quality of signals being recorded in the field and have a real value between zero and one in the range of frequencies being measured. The value of one indicates a high signal-to-noise ratio (i.e., perfect correlation between the two signals) while values of zero represents no correlation between the two signals. The coherence function is a ratio of the output power caused by the measured input to the total measured output which is defined as:

$$\gamma^2(f) = \frac{G_{yx}(f) \cdot G^*_{yx}(f)}{G_{xx}(f) \cdot G_{yy}(f)} \tag{10}$$

5. A linear relationship between the phase different and frequency from the transfer function spectrum is then derived. The phase velocity is examined as a function of distance from the slope value (*m*). This relationship can be written as:

   $$\phi = \left|\frac{360\mathrm{D}}{\mathrm{V_{ph}}}\right| f = mf \tag{11}$$

   By Eq. 11, one can easily determine $\mathrm{V_{ph}}$ by performing a least-square linear regression over the frequency range in the transfer function spectrum and the slope of the best-fit line (*m*) can be obtained. The phase velocity of surface wave propagation is independent of the wavelength for up to a wavelength approximately equal to thickness of the uppermost layer. The range of wavelength to be used can be estimated from the phase velocities (V_{ph}) of the material anticipated at the site:

   $$\lambda = \frac{V_{ph}}{f} \tag{12}$$

   where f is the frequency.
6. If one simply generates high frequency waves and assumes that properties of the uppermost layer are uniform, the dynamic elastic moduli of the pavement materials can easily be determined as follows:

   $$\mathrm{E} = 2\frac{\gamma}{g}V_S^2(1+\mu) = \frac{\gamma}{g}\left|\mathrm{KV_{ph}}\right|^2 \tag{13}$$

   $$K = (1.13 - 0.16\mu)\sqrt{\frac{2(1-\mu)}{(1-2\mu)}} \tag{14}$$

   where E is the dynamic elastic modulus, respectively, $\mathrm{V_S}$ is the shear wave velocity, $\mathrm{V_{ph}}$ is the phase wave velocity, g is the gravitational acceleration, γ is the total unit weight of the material and μ is the Poisson's ratio.

3 Results and Discussion

3.1 Stiffness and Elastic Modulus

The WSSW measurements were carried out at 12 sites on existing asphalt pavements. A typical result of received signals from field measurement was shown in Fig. 3. The body waves (Primary and Secondary wave) and surface wave (Rayleigh wave) are clearly shown in both signal recordings. Therefore, the Gaussian Derivative (GoD) continuous wavelet transform (CWT) was employed on signals for generating a time-frequency (TF) plot. Both CWT plots may overcome on identification problem of the spectral characteristics of non-stationary signals measured in two receivers. The typical CWT spectrogram for received signals with an improved time-frequency resolution is shown in Fig. 4. From Fig. 4, two main energy events at different frequency bands were also clearly detected which may result in both low and higher mode of seismic waves. It is able to observed that lower frequency energy was found in the range of 2.8–16 kHz in CWT spectrogram. This spectrum range is identified as surface wave signals. The level and frequency range of these signals were determined by independent-measurement of high level energy in surface wave propagation (up to 60% of total wave energy). Thus, the other energy event is identified as wave mode from direct and reflected body waves which was found in more than 20 kHz. The dominant wave energy found in CWT spectrogram at interested frequency range of surface waves can be clearly captured. The TF of GoD-CWT provides good resolutions at high frequencies of signals. It is also effective in the detection of frequency bandwidth of wave groups using various derivation order of this mother wavelet (GoD).

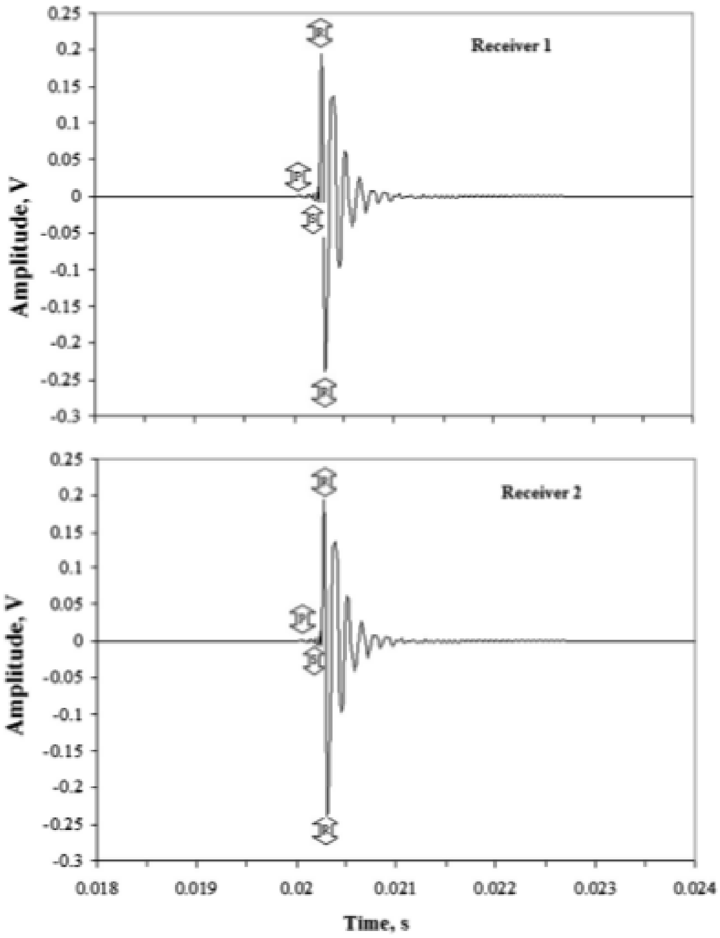
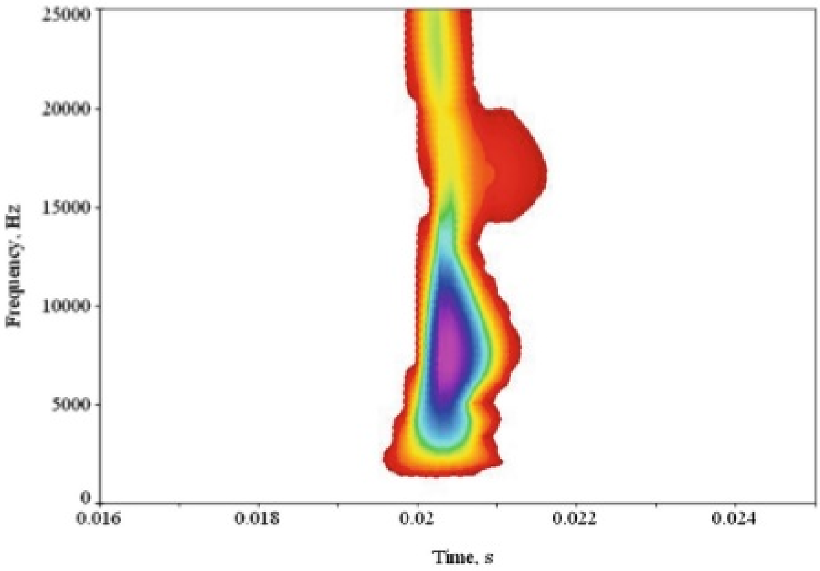
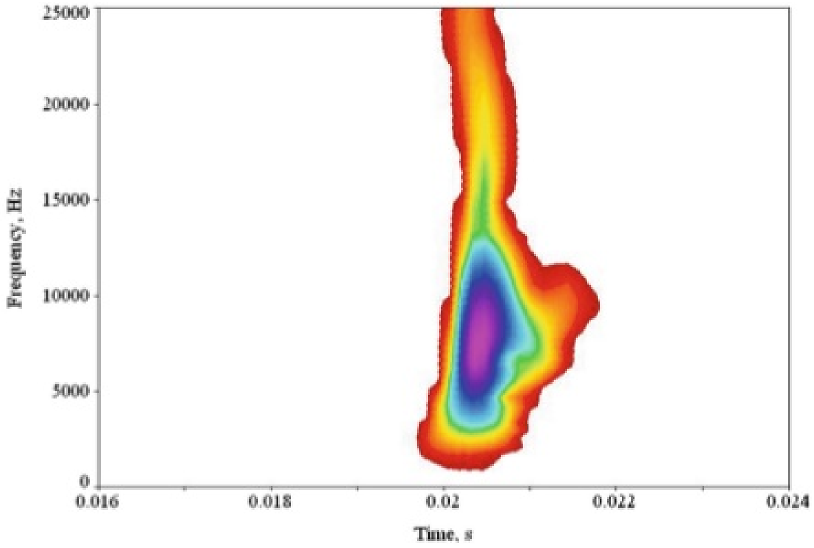


Fig. 3. Signal from WSSW measurement on a pavement structure

Based on both TF spectrograms (Fig. 4), the phase different between two signals for every wave frequency were then calculated. As a result, a transfer function spectrum on wrapped phase different curve was obtained as given in Fig. 5. The phase data



(a) CWT Spectrogram from receiver 1



(b) CWT Spectrogram from receiver 2

Fig. 4. Time-frequency plot of received signals from measurement

oscillates between −π and π radian (−180 and 180 degrees). This is the standard illustration of spectrum presenting phase data because the detail variation in data can be observed in a small space.

Figure 5 also shows that the phase different curve reveals a smooth trend of variation in phase with frequency up to a frequency of 25 kHz. It indicates the high-frequency surface waves were detected representing the high stiffness of the asphalt concrete surface layer on a pavement structure. The quality of phase data is also controlled by the coherence function. As shown in Fig. 6, the phase data up to frequency of 20 kHz have the value of coherence magnitude above 0.98.

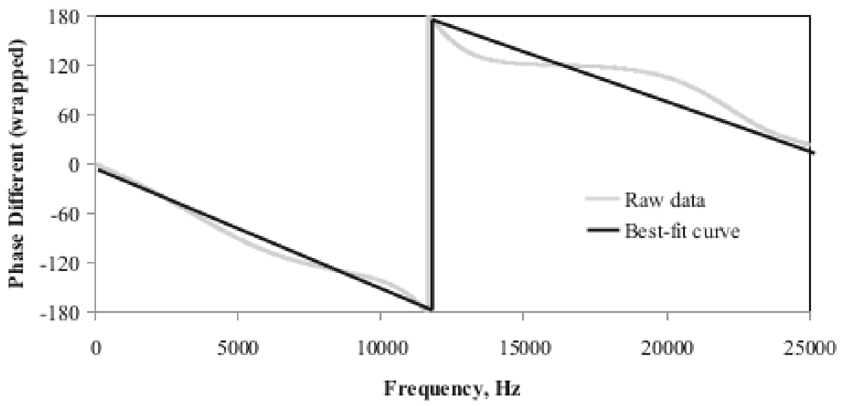


Fig. 5. Comparison between raw data and best-fit curve of wrapped transfer function spectrum from measurement

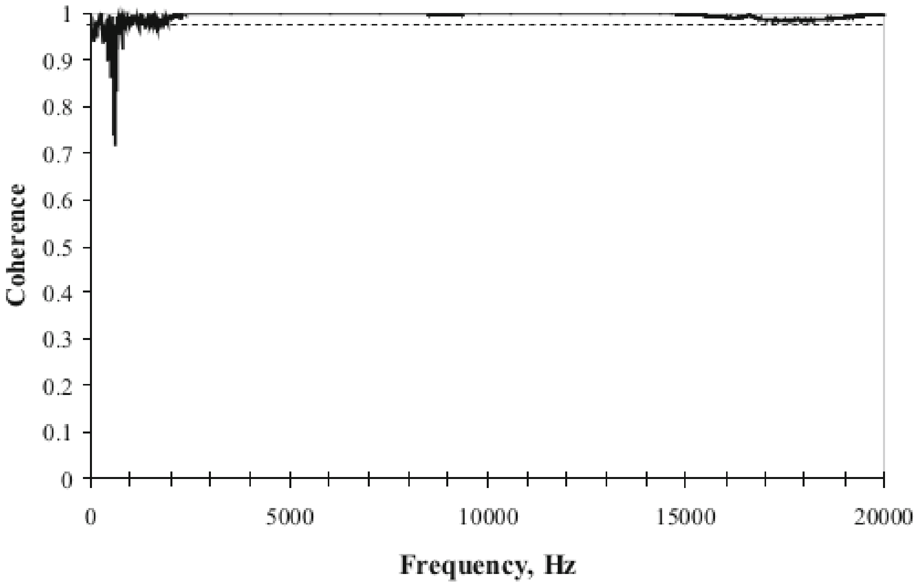


Fig. 6. Coherent function spectrum of received signals from measurement

In order to obtain the modulus value of the surface layer, the smoothed fitting process of weighing function was used. The fitted curve between the raw and the smoothed phase spectrum is shown in Fig. 5. Thus, the phase data is unwrapped by adding the number cycles to each phase. The unwrapped of the raw phase spectrum is also shown in Fig. 7. The unwrapped phase spectrum is smoothed by the linear regression as the best fit curve to the raw data. The slope of the line is more or less constant with frequency. A line is fitted to the curve in the range of the frequency corresponding to wavelengths shorter than the thickness of the surface layer. Slope value of the line can be used to determine the elastic modulus of the surface layer of the pavement profile using Eqs. 11, 13 and 14.

From Fig. 7, the slope (m) of best-fit curve is found to be 0.0140. Consequently, the phase velocity can be calculated using Eq. 13 which is found to be 1028.57 m/s. Based on the phase velocity, field configuration data and material parameters, such as of

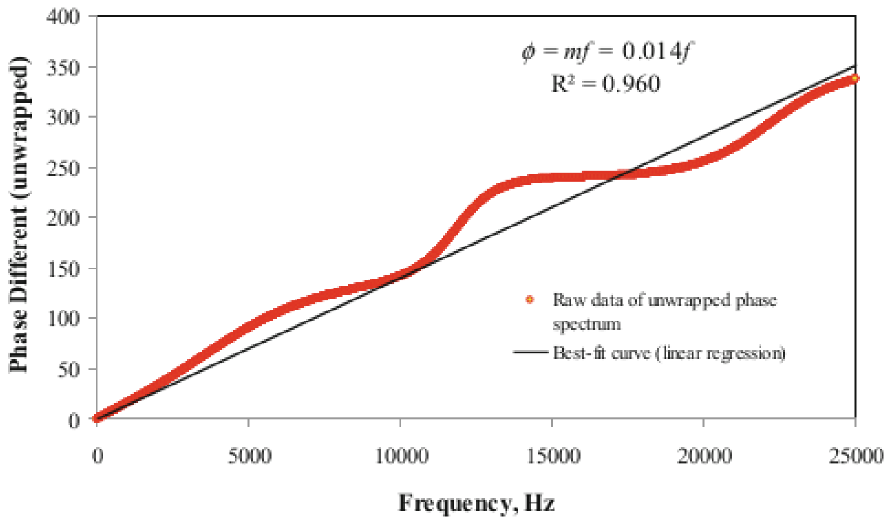


Fig. 7. Comparison between raw data and best-fit curve of unwrapped transfer function spectrum from measurement and slope analysis to obtain *m* value

receiver spacing (d_2) of 5 cm, Poisson's ratio of asphaltic layer of 0.25 and unit weight for pavement material (AC) of 2,200 kg/m^3, the elastic modulus of asphaltic (AC) surface layer is obtained as 845,662,040.80 kg/m^2 or 8456.62 MPa.

The result shows that the elastic modulus of AC layer can be easily determined using the WSSW technique. However, the value of elastic modulus presented is relatively high. It is due to the seismic technique measures the dynamic stiffness at very low strain level (less than 103%). In this level, the material modulus behavior can be assumed as a constant and have only a maximum value. To illustrate the usefulness and sensitivity of this approach in testing the surface layer, changes in the stiffness of the existing surface and the overlay layer of the pavement were measured in situ. Figure 8 shows that the different stiffness of an existing and overlay surface layer from the measured profile can be investigated well. Based on these results, it can be summarized that the stiffness changes in the surface layer were easily, non-destructively, and fast measured by the WSSW technique.

3.2 Validation with the SASW Method

In order to validate the results from the WSSW test, the spectral-analysis-of-surface-wave (SASW) analysis was conducted at same locations of a road pavement. In this method, a set of transient impact sources was used to generate surface wave energy that propagates horizontally near the surface layer of the pavement. The phase differences of signal data were obtained from the cross-power spectrum. Thus, the phase information was then unwrapped to produce the dispersion curve of the phase velocity versus wavelength. An inversion process was then iteratively employed to confirm the experimental dispersion curve from the theoretical model established. A 3-D stiffness matrix model (Rosyidi 2007) was employed in the SASW inversion analysis. Final stiffness profile was obtained after 16 times of iteration with the root-mean-square error (RMS) of 35.47 m/s or average deviation of about 5.92%.

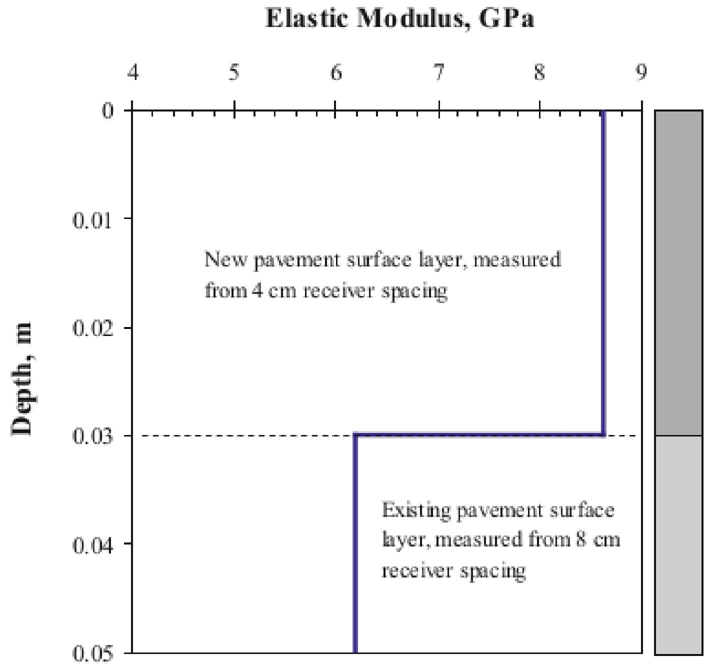


Fig. 8. Comparison between elastic modulus of an overlay and existing surface layer at pavement roads, Indonesia

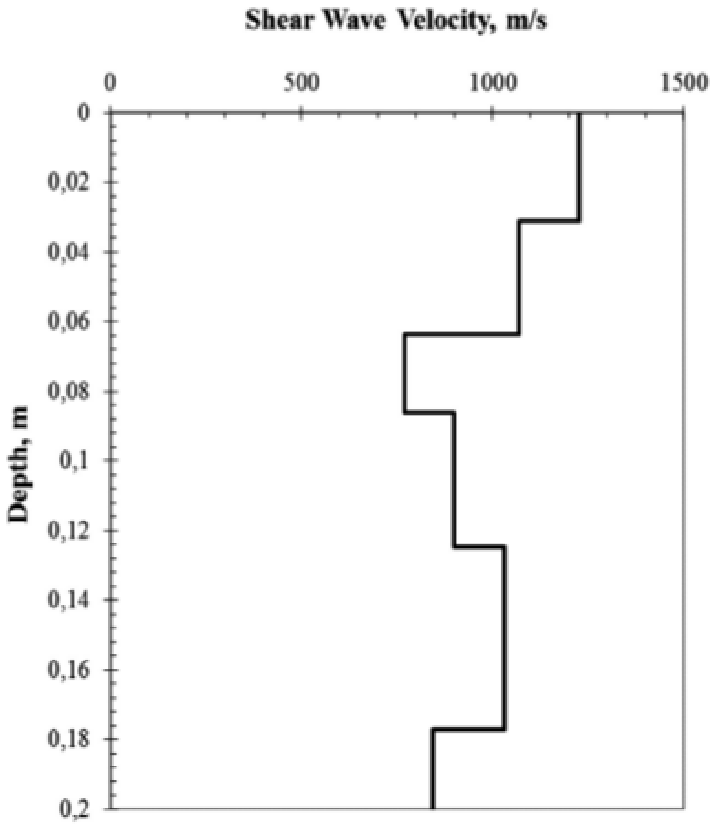


Fig. 9. The shear wave velocity profile from inversion of the experimental dispersion curve

The equivalent shear wave profile from the result of the inversion is shown in Fig. 9 and using the dynamic material equation, its equivalent dynamic elastic modulus profile is given in Fig. 10. A modulus profile as shown in Fig. 10 is only given to 10 cm depth of pavement structure due to the asphaltic layer was indicated at this level. A good agreement of elastic modulus resulted from the WSSW and the SASW method is also presented in Fig. 10. The result shows that the difference between both methods is calculated at 0.01% and 1.14% for first and second layer of pavement surface layer, respectively.

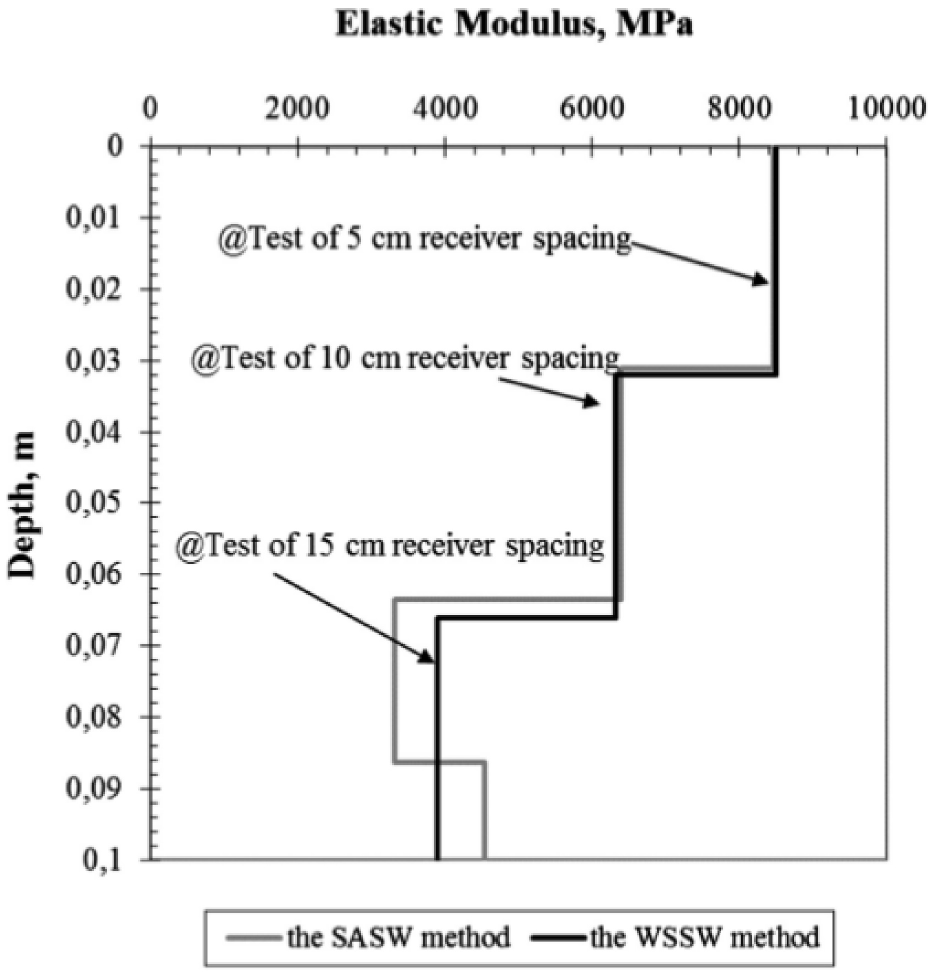


Fig. 10. The dynamic elastic modulus of the pavement profile from the SASW method and its comparison with the WSSW method

The falling weight deflectometer (FWD) method was also employed to validate the elastic modulus of pavement surface layer from the WSSW test. The elastic modulus of pavement surface layer obtained from both measurements is shown in Fig. 11. The elastic modulus obtained from the WSSW is higher comparison with value determined by the FWD. As mentioned earlier, the modulus measured at very low strain levels associated with surface wave method is in maximum value and it is independent from strain amplitude. In addition, the high frequency used in the seismic result in higher values of stiffness for pavement material. In the case of FWD, the modulus was measured at frequency of around 30 Hz (Fig. 12).

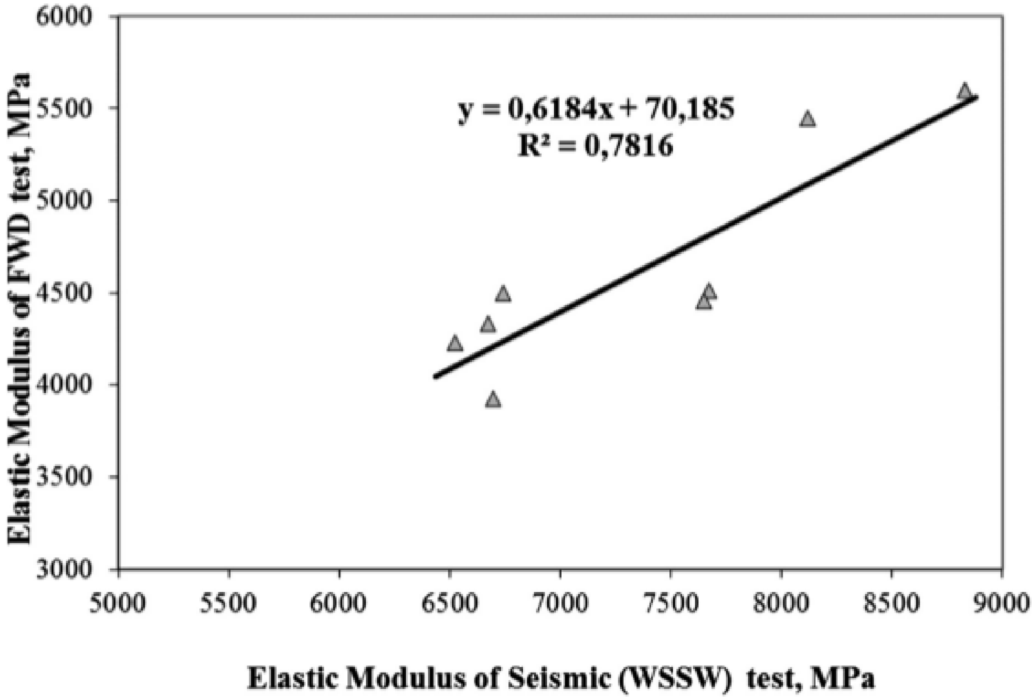


Fig. 11. Comparison elastic modulus of surface layers from the SASW test compared to the FWD test at Purwakarta State Road, Indonesia

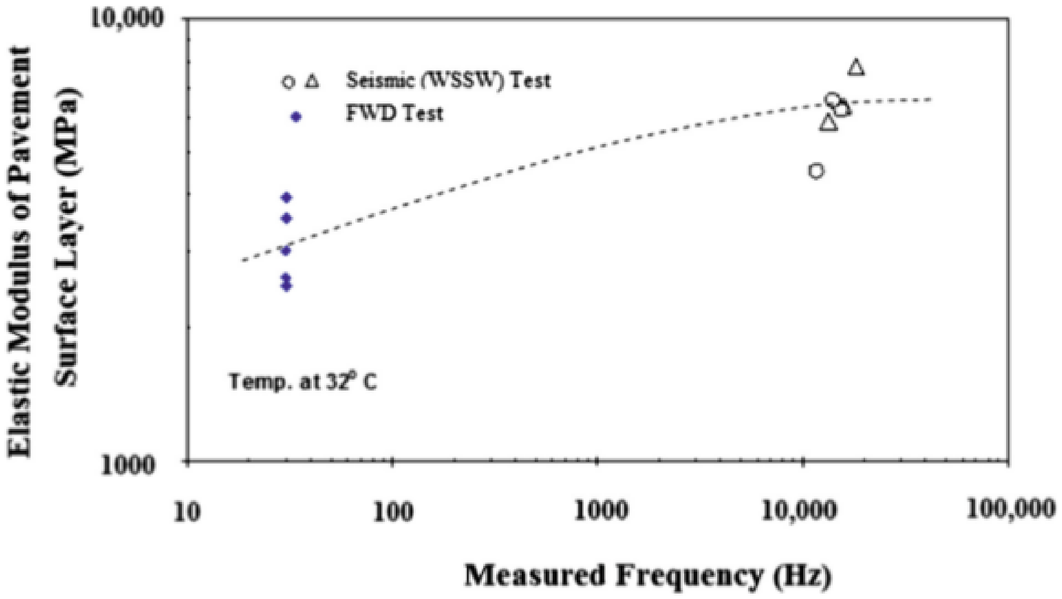


Fig. 12. Influence of frequency on the small strain elastic modulus of asphalt concrete at measured temperature of 32 °C at Purwakarta Road, Indonesia

4 Conclusions

The dynamic elastic modulus profile obtained from the proposed technique of the wavelet-spectrogram analysis of surface waves (WSSW) were presented in this paper. This technique improves the conventional SASW measurement testing and was used for investigation in the complex pavement structure. In this paper, the identification, denoising and reconstruction of the wave response spectrum from seismic surface wave propagation using time-frequency analysis of continuous wavelet transforms is presented. The spectrogram could be used to clearly identify the various events of interest mode of the seismic surface waves. By the simple calculation on phase spectrum from the surface wave data, the elastic modulus of the surface layer can be obtained without the complex calculation of the inversion process. The calculation is easy and can be simply implemented. This technique is also a very sensitive non-destructive testing (NDT) to monitor the change of the modulus of the existing surface and overlay layers.

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Wavelet-Spectrogram Analysis of Surface NDT Pavement

ORIGINALITY REPORT

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