

Simultaneous in situ stiffness and anomalies wavelet

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Simultaneous in-situ stiffness and anomalies measurement on pavement subgrade using tomography surface waves technique

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Abstract

Non-destructive testing (NDT) has been developed as an effective tool in road evaluation system in order to in-situ assess the stiffness parameter of pavement layer, particularly in conducting a quick assessment on soil subgrade layer. The NDT method based on the seismic surface wave measurement has been recently developed and applied for material evaluation of road-pavement, i.e. the shear wave velocity, Poisson's ratio and dynamic elastic modulus. In this paper, an improved technique of tomography surface waves measurement for simultaneously evaluation of stiffness and anomalies of pavement soil-subgrade is presented. The method performs the time-frequency spectrum analysis on recorded seismic wave data, which is non-destructively sampling the subgrade layers properties. An interactive wavelet analysis is used in the spectrum analysis to produce the real phase velocity and its corresponding shear wave velocity. Using principal of stress-strain material in elastic behavior, the elastic modulus parameter of soil-subgrade layers is then generated. This method is improved for producing the 2-D elastic modulus profile and at the same time, it shows the structure anomalies in the investigated subgrade layers. The higher elastic modulus values can be found in the subgrade layer with more homogeneous soil densities that may be produced from a good degree of compaction. While the lower elastic modulus can be identified in the subgrade layers which are having many structural anomalies. From this study, it can be shown that the tomography seismic surface wave technique is able to simultaneously determine the stiffness and structure anomalies within existing road pavement. Thus, this method can be potentially advanced and developed as an innovative material evaluation device for pavement structures.

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Keywords: tomography surface wave; pavement evaluation; anomalies; stiffness

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1. Introduction

In the pavement management system (PMS), an important aspect of management process is to determine the current and to predict the future structural capacity of the pavement. In order to establish the structural capacity of the existing roads, accurate information of the layer elastic moduli and thicknesses are needed. Those parameters are used to calculate load capacity to predict the performance of roads in order to select and design appropriate rehabilitation. Nowadays, the need of accurate, cost-effective, fast and non-destructive testing (NDT) evaluation of pavement system 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. Comparing to the NDT methods, conventional methods of pavement failure investigation include visual observation of base course condition, extraction and examination of core samples from rutted sections and analyzing lab test results from the cores. These methods are expensive and required a lot of work and time to be performed.

One of NDT methods is the spectral analysis of surface wave (SASW) which is a geophysical testing method based on the dispersion of Rayleigh waves (R waves) to determine the shear wave velocity corresponding to dynamic elastic modulus and depth of each layer of the pavement profile. The SASW method has been used for pavement layer thickness evaluation, concrete bridge condition assessment, elastic and shear modulus measurement of pavement materials, soil density assessment [1]. The results of these studies show that the SASW method can be a useful tool for pavement evaluation and inspection works.

Herein, the study introduces the tomography surface wave technique which is an innovation seismic method combined between the SASW method and tomography technique to evaluate the soil subgrade pavement condition and its possible anomalies or deterioration. Study was carried out in 83 observed sites of existing highway pavement in Raya Cipatik Road, Soreang and Jalan Cagak Road, Subang, West Java. The FWD method was also employed to validate the elastic modulus of pavement soil subgrade produced from the analysis. Results of this study used in developing nondestructive and cost-effective measures for pavement rehabilitation.

2. Research Method

The tomography surface waves technique is an improved system on the spectral analysis of surface waves (SASW) method. The technique is originally based on the measurement of R wave particles in heterogeneous media. The R wave energy from the point source propagates mechanically along the surface of media and their amplitude decrease rapidly with depth. R wave velocity has uniqueness characteristic which it varies with frequency in different stiffness layers of solid medium. This phenomenon is termed dispersion where the frequency is dependent on R wave velocity. The shorter wavelength of high frequency penetrates the shallower zone of the near surface and the longer wavelength of lower frequency penetrates deeper into the medium. The dispersion of R wave velocity versus wavelength can be identified through phase information of the transfer function spectrum generated from the field measurement.

2.1. Field measurement

The general measurement system of tomography surface waves technique is illustrated in Figure 1. Several impact sources on a pavement surface are used to generate R waves. These waves are detected using two until four accelerometers where the signals are recorded using an analog digital recorder. In this study, the short receiver spacings with combination of 5, 10 and 20 cm with a high frequency source (ball bearing) were used to sample the pavement surface layers while the long receiver spacings of 20, 40 cm and 80, 160 cm with a set of low frequencies sources (a set of hammers) were used to sample the base and subgrade layers, respectively. Several configurations of the receiver and the source spacings are required in order to sample different depths and configuration of mid-point receiver is recommended for tomography surface wave technique.

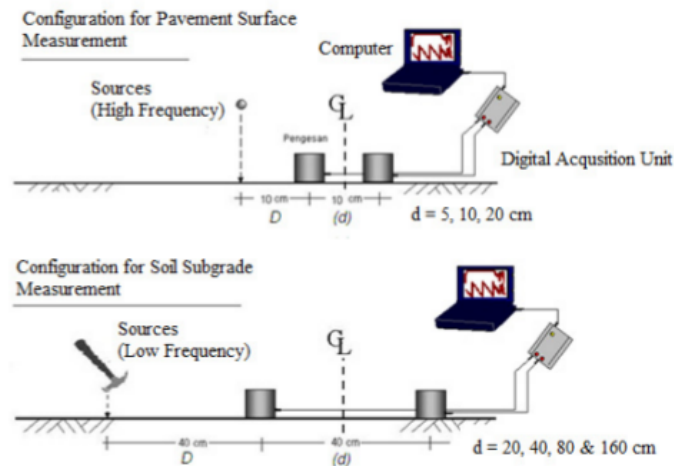


Fig. 1. Field measurement of tomography surface wave technique for pavement and soil subgrade measurement

2.2. Data analysis

All the data collected from the recorder are transformed using the *Fast Fourier Transform* (FFT) and *Continuous Wavelet Transform* (CWT) algorithm to frequency domain. Two important spectrums used in this measurement, i.e., the coherence function and the phase information of the transfer function were configured in the data analysis. The coherence function is an easy way to visually examine the quality of signals being recorded in the field measurement and the transfer function spectrum is used to obtain the relative phase shift between the two signals in the range of the frequencies being generated.

The CWT filtration was performed by using on the wavelet spectrogram for obtaining the time and frequency localization thresholds. 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 [2]:

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

where $\overline{\psi}$ is the complex conjugate of ψ , $F_W(\sigma, \tau)$ is the time-scale map. The convolution integral from Eq. (1) can be computed in the Fourier domain.

In this study, the CWT filtration is developed base on the simple truncation filter concept which only considers the passband and stopband. 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. Proposed design of the CWT filtration can be written as:

$$f(s) = \begin{cases} 0, & 1 \leq s \leq F_l \\ 1, & F_l \leq s \leq F_h \\ 0, & F_h \leq s \leq N \end{cases} \quad f(u) = \begin{cases} 0, & 1 \leq u \leq T_l \\ 1, & T_l \leq u \leq T_h \\ 0, & T_h \leq u \leq N \end{cases} \quad (2)$$

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. The phase difference from reconstructed signals at each frequency is then calculated in order to develop the phase spectrum for the experimental dispersion curve. The phase difference data can be obtained from:

$$\phi_n(f) = \arctan \left(\frac{\Im \{s^{-1} W_n^{XY}(s)\}}{\Re \{s^{-1} W_n^{XY}(s)\}} \right) \quad (3)$$

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

The time of travel between the receivers for each frequency from wavelet cross spectrum can be calculated by:

$$t(f) = \frac{\phi(f)}{360f} \quad (4)$$

where f is the frequency, $t(f)$ and $\phi(f)$ are respectively the travel time and the phase difference in degree at a given frequency. The distance of the receiver (d) is a known parameter. Therefore, R wave velocity, V_R or the phase velocity at a given frequency is simply obtained by:

$$V_R = \frac{d}{t(f)} \quad (5)$$

and corresponding wavelength of the R wave, L_R may be written as:

$$L_R(f) = \frac{V_R(f)}{f} \quad (6)$$

By unwrapping the data of the phase angle from the transfer function, a composite experimental dispersion curve of all the receiver spacings are generated. By repeating the procedure outlined above and using equation (4) through (6) for each frequency value, the R wave velocity corresponding to each wavelength is evaluated and the experimental dispersion curve is subsequently generated.

The actual shear wave velocity of the pavement profile is produced from the inversion of the composite experimental dispersion curve. An inversion procedure uses stress-wave propagation theory. The propagation theory models a theoretical dispersion curve, which is compared with experimental dispersion curve. In this study, an automated forward modeling analysis of the 3 dimensional (3-D) dynamic stiffness matrix method [3] was used for generating the theoretical dispersion curve. Consequently, the theoretical dispersion curve is compared with the experimental dispersion curve. If the two dispersion curves do not match, the pavement profile is adjusted and another theoretical dispersion curve is calculated. An interactive iteration procedure, i.e., maximum likelihood method [4] is then conducted until the two curves match, and then the associated profile is considered the representative pavement profile.

2.3. Stiffness prediction

The material stiffness of pavement, i.e., dynamic elastic moduli can be obtained from the following relationship between the shear wave velocity (V_s), the gravitational acceleration (g), the total unit weight (γ) and the Poisson ratio (μ):

$$E = 2 \frac{\gamma}{g} V_s^2 (1 + \mu) \quad (7)$$

where E is the dynamic elastic modulus. [5] explained that the modulus parameter of material is maximum at a strain below about 0.001 %. In this strain range, modulus of the materials is also taken as constant.

3. Results and Discussion

3.1. Elastic modulus of soil subgrade

From the recorded seismic 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 can be also identified as an effect of environmental noise which maybe produced from ground or traffic 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, 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. In other word, the conventional spectral analysis of non-stationary signal of seismic waves cannot describe the local transient event due to averaging duration of signals. It also cannot instantly separate the event of true seismic waves from noise signals. Consequently, it is difficult to capture the correct phase information in transfer function of 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. From CWT on analysis both signals, its phase spectrum can be clearly displayed as Figure 3. Based on phase difference from multiplication on both spectrum functions at each frequency, the experimental dispersion curve of SASW measurement from several sites can be generated. Figure 2 shows an example of phase difference versus frequency plot produced from the CWT analysis from this study. It was measured for 80 cm receiver spacing which is employed for detecting the pavement soil subgrade.

An example of the shear wave profile from the result of the inversion process in the SASW method on the existing pavement is shown in Figure 3. Using the dynamic material equation (Equation 7), its equivalent dynamic elastic modulus profile is given in Figure 3. Each layer of the pavement profile was clearly detected by the 3-D inversion analyses compared to the core profile. Particularly for pavement surface layer, between the overlay and original layer was distinguished well.

The FWD method was also employed to validate the subgrade elastic modulus produced from the SASW [17](#). The elastic modulus of subgrade layer obtained from FWD and SASW measurements are shown in Figure 4. [The elastic modulus](#) of the subgrade [layer](#) obtained from the SASW is larger 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. Second, the high frequency used in the SASW result in higher values of stiffness for subgrade material. In the case of FWD, the modulus was measured at frequency of 30 Hz.

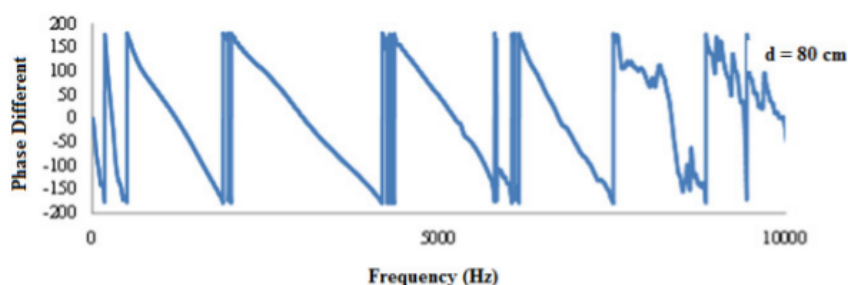


Fig. 2. An example of phase difference and frequency spectrum produced from teh CWT analysis for 80 cm receiver spacing of observed road site

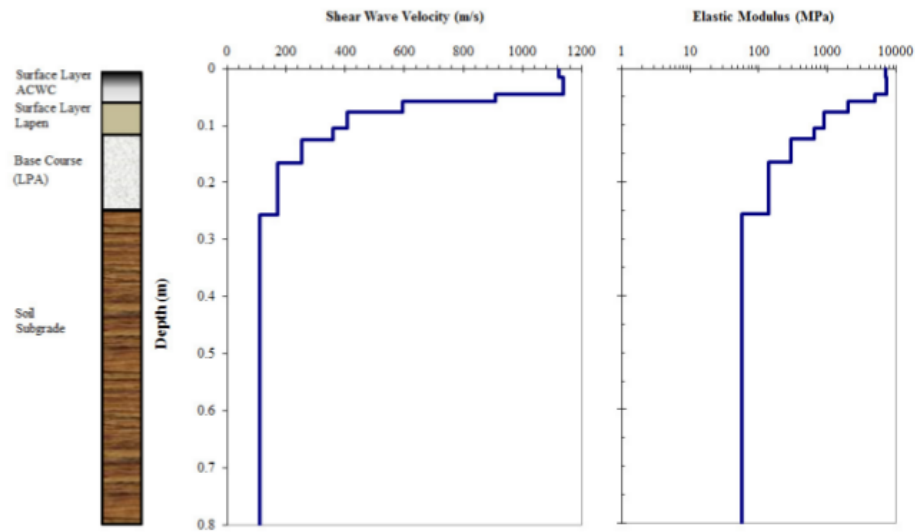


Fig. 3. An example of shear wave velocity profile and its equivalent elastic modulus on the existing pavement of observed road sites

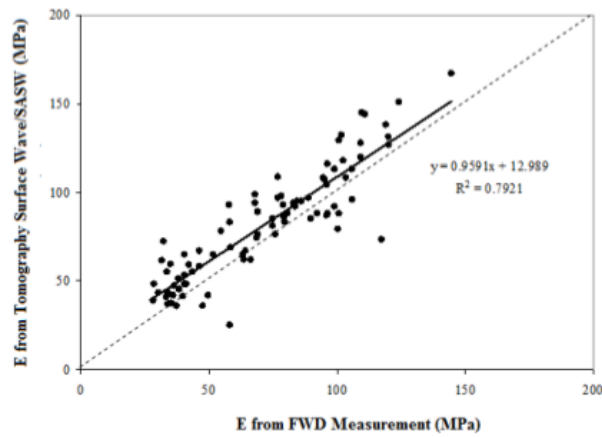


Fig. 4. Elastic modulus of subgrade layers from the Tomography Surface Wave/SASW test compared to the FWD test at observed road sites

3.2. 2-D tomography profile

The one dimensional shear wave velocities and its equivalent elastic modulus profile are obtained from the inversion analysis (Fig.3). The inversion of the dispersion of subsequent movement of the source to geophone array then produces the final two dimensional images as a 2-D tomography profile which is presented in Fig. 5. From 2-D tomography profile can be shown that the structure anomalies is investigated in soil subgrade layers. The higher elastic modulus values can be found in the subgrade layer with more homogeneous soil densities that may be produced from a good degree of compaction. While the lower elastic modulus can be identified in the subgrade layers which are having many structural anomalies. From this study, it can be shown that the tomography seismic surface wave technique is able to simultaneously determine the stiffness and structure anomalies within existing road pavement.

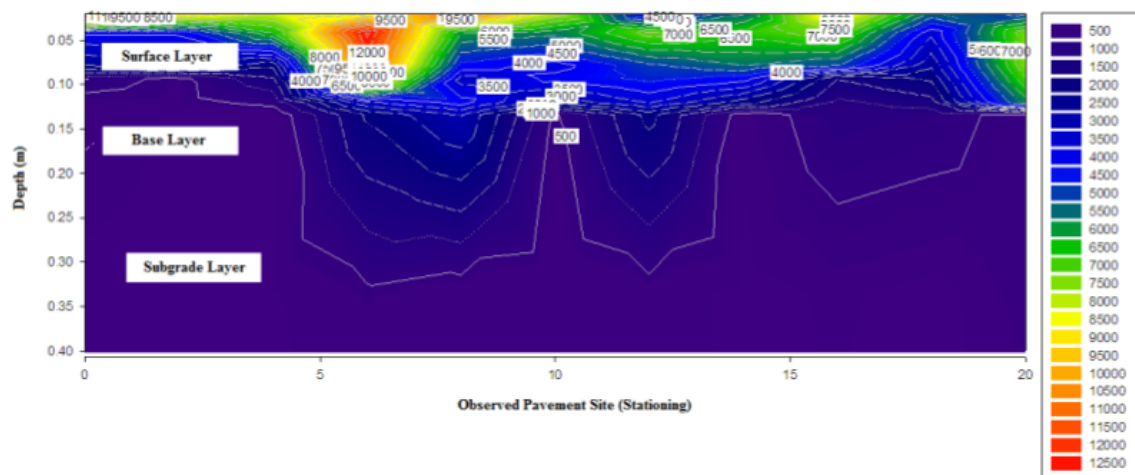


Fig. 5. Tomography profile of elastic modulus of subgrade layers from an observed road site

4. Conclusion

The simultaneous measurement of stiffness and anomalies in the pavement soil subgrade layer using tomography surface wave method has been introduced in this study. The method is an innovative development from the spectral analysis of surface wave (SASW) method. The tomography surface wave method can be potentially advanced and developed as an innovative material evaluation device for pavement structures. However, due to the small strain levels and high frequency involved in the seismic measurement, the values of elastic modulus of the soil subgrade are higher compared to modulus obtained from FWD measurement.

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