In-situ Measurement of Pavement Moduli

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IN-SITU MEASUREMENT OF PAVEMENT MODULI USING SURFACE WAVE-TOMOGRAPHY METHOD

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Abstract

The surface wave-tomography method (SWT) method was applied for in situ measurement of the dynamic material parameters, i.e. the dynamic elastic modulus of pavement structure. The SWT method is a non destructive-tests (NDTs) developed from the Spectral-Analysis-of-Surface-Waves (SASW) method. A procedure to use in the SWT method was also introduced. In order to validate the elastic modulus obtained from the SASW method, a deflection-measuring device i.e. the falling weight deflectometer (FWD) test was used to determine the soil subgrade modulus at same sites where the SWT method was performed. From this study, it is shown that the SWT method is able to successfully determine the 2 D tomography stiffness profile of the road pavement. Thus, the surface wave-tomography method can be potentially advanced and developed as an innovative material evaluation device for pavement structures.

Keywords: *surface waves; NDT; pavement modulus; tomography*

Introduction

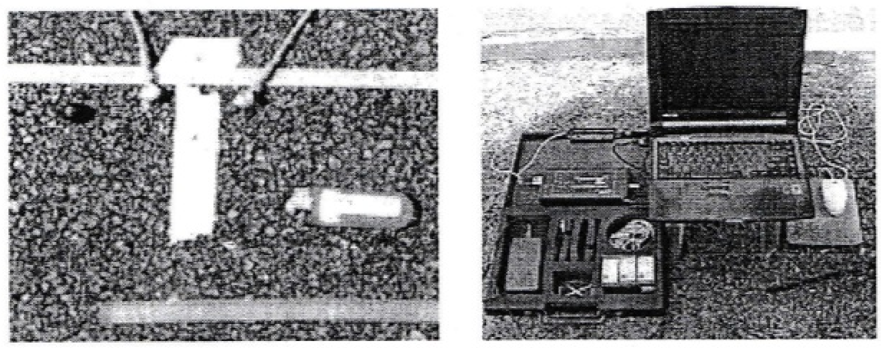
Highway pavements undergo continuous destruction from the time it is open for use. Thus it is important that the performance of these pavements be assessed as frequent as possible to ensure that it could continue to serve its purpose. There are two methods to determine the performance of pavement structures i.e. the destructive testing (DT) and the non-destructive testing (NDT). The DT method (i.e. resilient modulus test, Marshall test) is more time consuming, destructive (coring required) and costly if applied in routine monitoring of road works. On the other hand, the NDT method is more economic and fast. The FWD method is an NDT method that measures the pavement moduli based on the concept of deflection. However, the method can be somewhat insensitive to the modulus of the pavement surface layer, especially for the cases of a thin surface layer on the order of a few centimeters thick or under those conditions where the bedrock is near the surface. The wave propagation method is also an NDT method based on the velocities of the seismic waves (primary, shear, Rayleigh and Love waves) that propagate in the media for determining of that pavement structure.

The Spectral Analysis of Surface Wave (SASW) is one of the wave propagation techniques that use the characteristics of the dispersion of Rayleigh waves (R waves) to determine the shear wave velocity, modulus and depth of each layer of the pavement profile. The SASW method is an in situ seismic technique used to evaluate the material stiffness of pavement layers at low strains. In pavement investigation, Heisey et al. (1982) and Nazarian & Stokoe (1984) started to conduct the measurement of the modulus and thickness using the SASW method. Thus, a considerable amount of theoretical and experimental research work has been successfully conducted by Rõesset et al. (1990). Rõesset et al. (1990), Rosyidi (2007, 2009), Rosyidi et al. (2004) and Taha et al. (2007) also studied the 3 D model in pavement investigation using the SASW analysis. Their result had shown that the 3 D model of SASW analysis was successful for complicated profile in the pavement system. In this study, analysis in the surface wave tomography method developed from the SASW method is presented in order for simultaneously determining the 2D shear wave velocity and elastic modulus tomography profile of pavement structure. Results from field studies are implemented for structural assessment of an existing road-pavement.

Methodology

Experimental Set Up

Various impact sources of 5 mm diameter of small ball bearing and hammers on a pavement surface were used to generate R waves. These waves are detected using two accelerometers (Figure 1a) transferred into digitalized-signal data by analog-digital converter. A notebook computer was provided in order to record the data for post processing (Figure 1b). Several configurations of the receiver and the source spacings are required in order to sample different depths. The best configuration in the SASW is the mid point receiver spacings as shown in Figure 2



(a) (b)

Figure 1. Field equipment for surface wave recording: (a) accelerometers for receiving the seismic wave displacement, (b) spectrum analyzer with an acquisition unit (Widodo & Rosyidi, 2009)

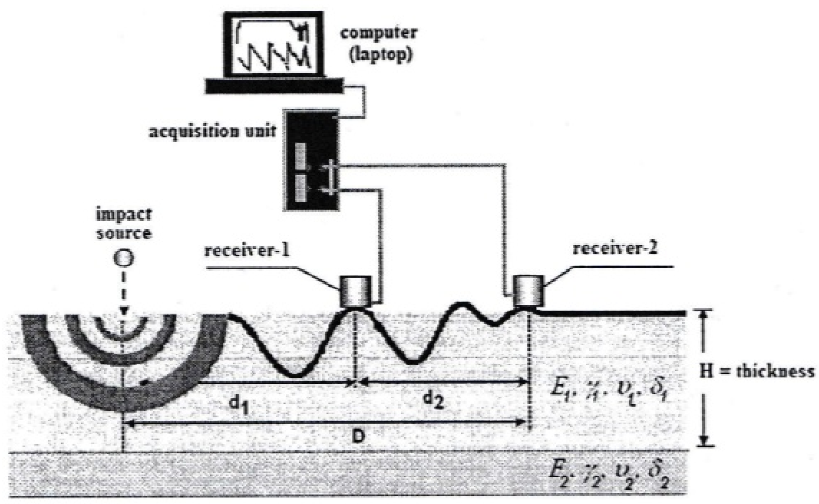


Figure 2. Configuration used for surface wave measurement

The short receiver spacings (4 and 8 cm) with a high frequency source (ball bearing) were used to sample the asphalt layers while the long receiver spacings (16, 32, 64, 100 cm) with a set of low frequencies sources (a set of hammers) were used to sample the base and subgrade layers, respectively. The surface wave testing was carried out on an existing flexible pavement of Cikampek – Purwakarta State (Province) Road, Indonesia. The pavement profile obtained from core drilling consists of an asphalt concrete layer (183 mm), crushed stone of base course (71 mm), sub-base course (190 mm) over a subgrade layer.

Procedure of SWT Analyses

A surface wave-tomography method is used to simultaneously determine the shear wave velocity and dynamic elastic stiffness of pavement structures. The procedure of data analyses in both measurements is described as follows.

Shear Wave Velocity

The seismic energy from the impact source was received by accelerometer receivers in time domain transient signal. All signals data collected from the recorder are transformed using the Fast Fourier Transform (FFT) to frequency domain which is displayed in the transfer function spectrum. This spectrum consists of the relative phase shift between the two signals (signal received in channel 2 as an output and channel 1 as an input) in the range of the frequencies being generated. By extracting the data of the phase angle from the wrapped transfer function, the time of travel between the receivers for each frequency can be calculated by:

$$t(f) = \frac{\phi(f)}{(360f)} \quad (1)$$

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

$$V_R = \frac{d}{t(f)} \tag{2}$$

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

$$L_R(f) = \frac{V_R(f)}{f} \tag{3}$$

By repeating the procedure outlined above and using equations (2) through (4) for each frequency value, the R wave velocity corresponding to each wavelength is evaluated and the experimental dispersion curve is subsequently generated. An example of experimental dispersion curve of interested receiver spacings for pavement structures is then generated (Figure 3).

The actual shear wave velocity of the 1D pavement profile is produced from the inversion of the experimental dispersion curve. In the inversion process, a profile of a homogeneous layer extending to infinity in the horizontal direction is assumed. The last layer is usually taken as a homogeneous half-space. Based on the initial profile, a theoretical dispersion curve is then calculated using an automated forward analysis of the 3-D wave propagation modeling generated by the dynamic stiffness matrix method (Kausel & Röesset, 1981). The theoretical dispersion curve is ultimately matched to the experimental dispersion curve of the lowest RMS error based on an optimization technique. An example of final theoretical dispersion curve with the best matching to experimental dispersion curve is also shown in Figure 3.

Dynamic Elastic Modulus

The dynamic elastic modulus of the pavement materials can then be easily determined from the following equation:

$$E = 2\frac{\gamma}{g}V_S^2(1+\mu) \tag{4}$$

where g is the gravitational acceleration, γ is the total unit weight of the material and μ is the Poisson's ratio. Nazarian and Stokoe (1986) explained that the modulus parameter of material is to be found in maximum moduli at a strain below about 0.001 %. In this strain range, modulus of the materials is also taken as constant.

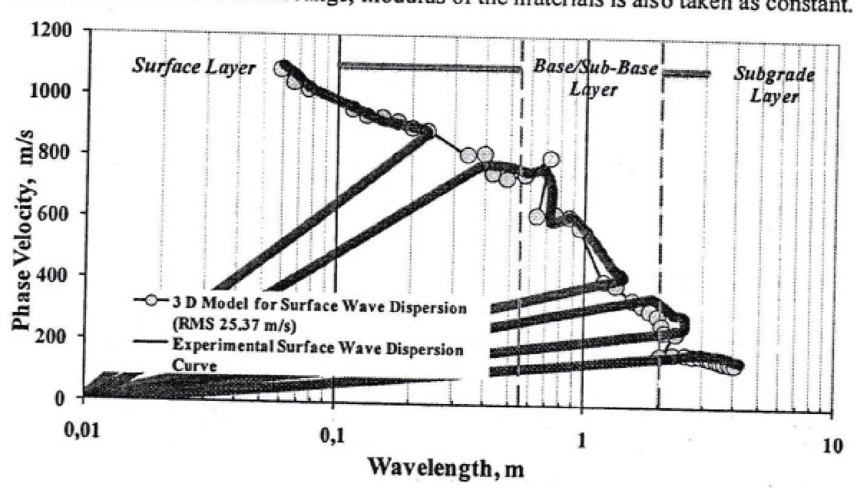


Figure 3. A typical experimental dispersion curve from a complete set of SASW (SWT) tests on the flexible pavement model compared to theoretical dispersion curve from 3 D wave propagation theory which shows the variation of wavelength with different phase velocities

2D Shear Wave Velocity Tomography Profile

The SWT analysis of the test data provides a 2D tomography of shear wave velocity and dynamic elastic modulus profile. The effective depth of measurement can be approximately investigated for every layer of pavement structure. The total length of measurement is obtained based on the series of 1D shear wave velocity profile at every segment of SWT tests. A 2D tomography profile is then analyzed using linear interpolation. Since a unique shear wave velocity profile is generated for each shot along the survey line, the individual profiles can be interpolated to create a single two-dimensional image representing lateral and vertical variations in shear wave velocity. No additional inversion is required. Interpolation can be performed using an equal weighting or variant weighting system.

Result and Discussions

Shear Wave Velocty and Elastic Modulus of Pavement Structure

Two examples of the shear wave profile from the result of the inversion process in the SWT method on the existing pavement are shown in Figure 4. The 1D shear wave velocity profiles show that each layer of the pavement profile is clearly detected by the 3-D inversion analyses with root mean square (RMS) of both profiles are 25.37 and 35.47 m/s, respectively. The first layer of pavement structure (asphaltic surface layer) is about 180 mm thick with a velocity up to 770 m/s. The second layer of base and sub-base layer were detected in 260 mm thick with a shear wave velocity ranging from 120 to 500 m/s, and the third layer of subgrade pavement is underlying formation of pavement structure with the shear wave velocity is observed from 100 to 120 m/s. The profiles are also in a good agreement with result from the core–drilled profile. Using Equation 4, the equivalent dynamic elastic modulus profile is given in Figure 4. Particularly for a pavement surface layer between the overlay and original layer was well distinguished.

Figure 5 and 6 show the 2D tomography profile of shear wave velocity and dynamic elastic modulus respectively. The 2D tomography shear wave velocity profile shows an investigation depth up to 600 mm (Figure 5). The top-most layer shows high velocity corresponding to the high dynamic elastic modulus in the upper about 180 mm of depth representing the asphaltic layers (S-wave velocity up to 500 m/s). Below 200 mm up to a depth 460 mm, the material has a velocity in the range 200–500 m/s, and decreases further to subgrade layer with shear wave velocity below 120 m/s. The result also shows that the elastic modulus of AC, Base, Sub-Base and Subgrade layer can be easily determined using the SWT technique. However, the value of elastic modulus presented is relatively high. The usefulness and sensitivity of this approach in testing the surface layer is also presented by detecting the changes in the stiffness of the existing surface and the overlay layer of the pavement measured in situ.

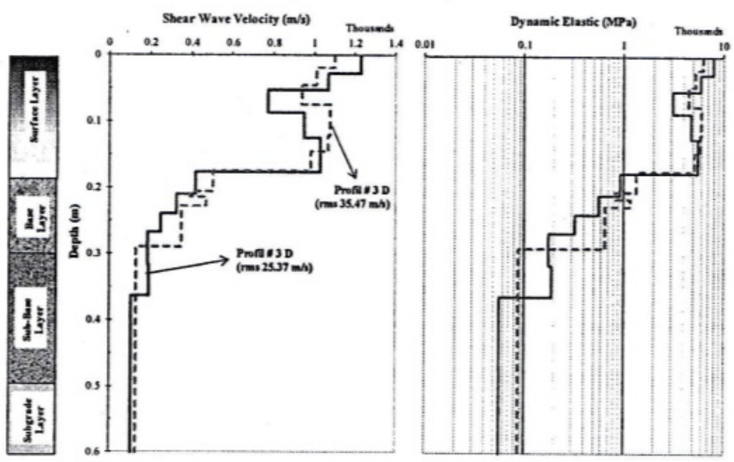


Figure 4. The shear wave velocity and dynamic elastic modulus profile on the existing pavement of Cikampek – Purwakarta State Road

The FWD method was also employed to validate the subgrade elastic modulus produced from the SWT test. The elastic modulus of subgrade layer obtained from FWD and SWT measurements are shown in Figure 7. The elastic modulus of the subgrade layer obtained from the SWT method is larger in comparison with value determined by the FWD. As mentioned earlier, the modulus using the SWT was measured at very low strain levels. Thus the associated the value of elastic modulus using surface wave is the maximum value and it is independent of the strain amplitude. In this level, the material modulus behaviour can be assumed as a constant (Nazarian & Stokoe, 1986).

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Second, high frequency used in the SWT method probably results in higher values of stiffness for subgrade material. In the case of FWD, the modulus was measured at frequency of 30 Hz.

Conclusions

This paper summarizes a new procedure in the surface wave-tomography (SWT) technique in order to in situ evaluation the 2D tomography profile of shear wave velocity and elastic modulus in each layer on an existing pavement profile. This technique is also a very sensitive non destructive testing to monitor the change of the modulus of the existing surface and overlay layers. 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 pavement layer are easily, non-destructively, and fast measured by the SWT technique.

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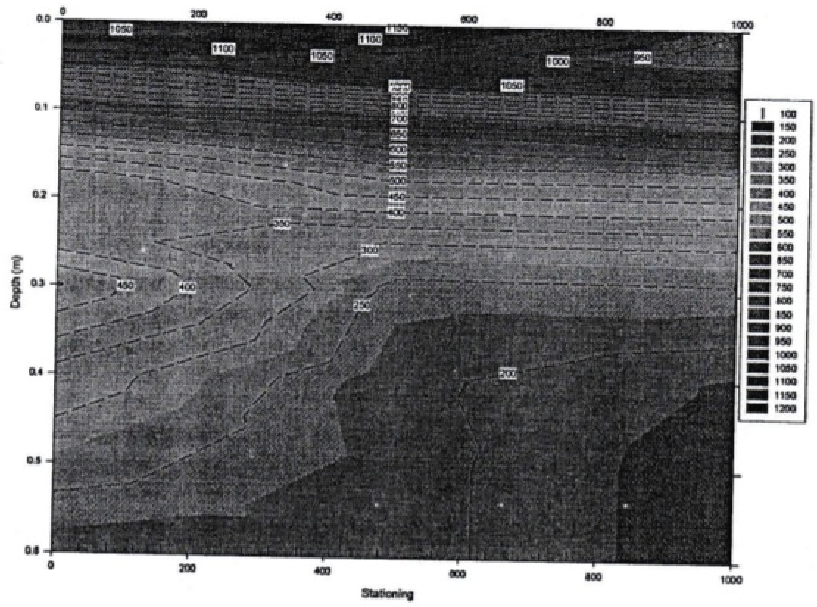

Figure 5. The 2D tomography of shear wave velocity profile on Cikampek – Purwakarta State Road

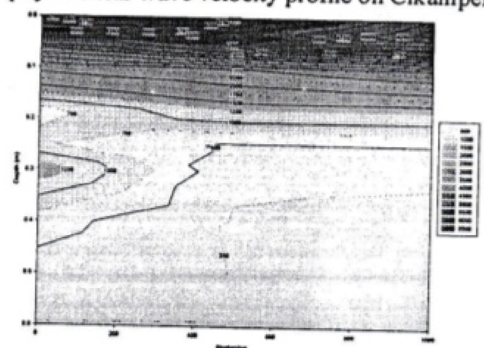

Figure 6. The 2D tomography of dynamic elastic modulus profile on Cikampek – Purwakarta State Road

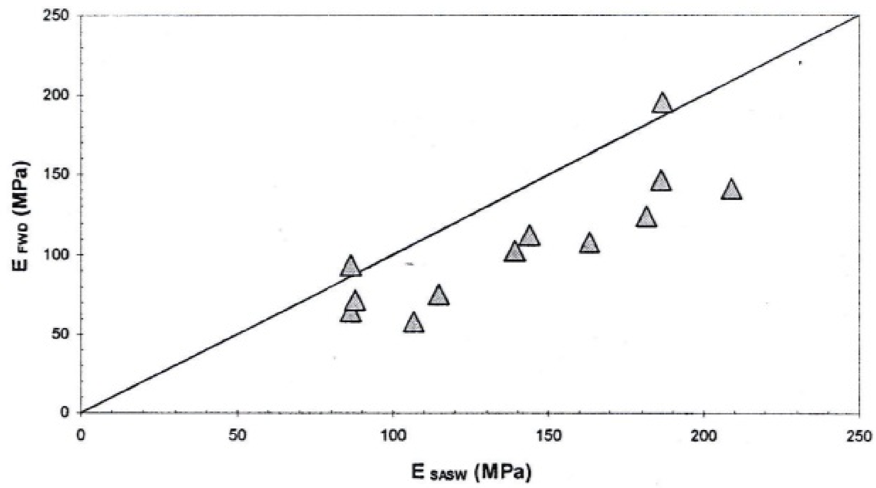

Figure 7. Elastic modulus of subgrade layers from the SWT test compared to the FWD test at Cikampek – Purwakarta State Road

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