THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

ISSN 1822-427X / eISSN 1822-4288
2015 Volume 10(2): 174–181

MEASUREMENTS OF THE ELASTIC MODULUS OF PAVEMENT SUBGRADE LAYERS USING THE SASW AND FWD TEST METHODS

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Abstract. In pavement management systems, deflection basin tests, such as the Falling Weight Deflectometer test, are common techniques that are widely used, while the surface wave test, i.e. the Spectral Analysis of Surface Wave test, is recently employed as an alternative technique in pavement evaluation and monitoring. In this paper, the performance of both dynamic non-destructive tests on pavement subgrade investigation is presented. Surface wave propagation between a set of receivers was transformed into the frequency domain using the Fast Fourier Transform technique and subsequently a phase spectrum was produced to measure the time lag between receivers. Using the phase difference method, an experimental dispersion curve was generated. Inversion analysis based on the 3-D stiffness matrix method was then performed to produce a shear wave velocity profile. The elastic modulus of pavement layers was calculated based on linear elastic theory. In the Falling Weight Deflectometer test, seven geophones were used to collect in situ deflection data. Based on a back-calculation procedure with the ELMOD software, the elastic modulus of each flexible pavement layer can be obtained. Both techniques are able to comprehensively investigate the elastic modulus of the subgrade layer in existing pavement non-destructively. The elastic modulus between the Spectral Analysis of Surface Wave method and the Falling Weight Deflectometer test on the subgrade layer is observed to be in a good agreement. A correlation of the elastic modulus of thesubgrade layer from both techniques is also presented.

Keywords: pavement, elastic modulus, spectral analysis of surface wave and falling weight deflectometer.

1. Introduction

Experience has shown that predictions and diagnosis of pavement integrity are significant, especially since destruction will continuously occur once highway pavements are open for traffic. To ensure the highway pavements continue to serve the purpose, it is very important to periodically evaluate their conditions. In general, there are two methods used to determine the performance of pavement structure: destructive testing (DT) and non-destructive testing (NDT). The DT method (i.e. resilient modulus test, Marshall test) has the advantage of examining actual in-service material. However, this conventional method is more time consuming, destructive (coring is required) and costly if applied in routine monitoring of road works (AASHTO 1993; Asphalt Institute 1986). It also provides only vertical information at certain points (Mulargia *et al*. 2014).

On the other hand, the NDT method is more economical and fast. The falling weight deflectometer (FWD) method is a NDT method that measures the pavement moduli based on the concept of a deflection bowl (Brown *et al.* 1987; Ullidtz 1987). The modulus of the subgrade structure can be assessed using the FWD method. The FWD is routinely used by pavement engineers to evaluate in-situ flexible pavement layer moduli (Hadidi, Gucunski 2010). It has been widely adopted by highway and airport agencies in pavement evaluations because of quick testing and standardize procedures (Kuo *et al.* 2015). Calculation and analysis of the deflection of the FWD test was conducted using the stochastic finite element method. However, this method can be somewhat insensitive to the modulus of the pavement surface layer, especially where the surface layer is just a few centimetres thick or where the bedrock is near the surface.

doi:10.3846/bjrbe.2015.22
http://www.bjrbe.vgtu.lt

A new method based on the spectral analysis of seismic waves, known as a spectral analysis of surface wave (SASW), is recently employed as an alternative technique in pavement evaluation and monitoring. This method has attracted the attention of researchers because it is fast, cheap, non-destructive and easy to operate (Goh *et al.* 2011). The SASW method is based on the Reyleigh waves that propagates in a media for the evaluation of the subgrade structure (Heisey *et al.* 1982; Joh 1996; Rosyidi 2004; Röesset 1990). By generating Rayleigh waves over a wide range of frequencies, the shear wave velocity of pavement and ground can be determined (Hazra, Kumar 2014). The SASW method has become a reliable technique to characterize the site and calculate the shear modulus of a layered system, such as layers of soil, asphalt and concrete (Cho 2002; Joh *et al.* 2008; Rosyidi 2004; Rosyidi *et al.* 2012). Previous studies conducted by Röesset *et al.* (1990), Joh (1996), Rosyidi (2004) and Taha *et al.* (2007) show that surface wave method has been utilized to find only modulus for subgrade layer of pavement. However in this study, the damping ratio parameter together with elastic modulus of subgrade pavement profile could also be determined by implementing the coupled analysis of surface wave method. Results from in situ measurements are presented in terms of the structural integrity assessment of the road.

2. Surface wave theory

The motion of propagating disturbance that is initiated in seismic testing is known as stress wave. SASW concentrates on utilizing Rayleigh wave propagation in its measurement. Among characteristics of this wave are: it has lower propagation velocity, lower frequency and high amplitude. In homogeneous half-space, Rayleigh waves are non-dispersive, however in real world, of heterogeneous material, Rayleigh waves are dispersive. Therefore we call this phenomenon 'dispersion', where this frequency is very much dependent on Rayleigh wave velocity. It is known that Rayleigh waves travel along the surface and do not lose much energy over large offset range, which makes them suitable to be used in surface measurement. SASW is sensitive to layer stiffness contrast, thus the method provides good sampling of thin material with high frequency waves. To sample from shallow materials to deeper depth of layers, a wide range of wavelength is needed. The sampling depth, and the wavelength range, will be used as a guide to estimate the distance between receivers. The wavelength can be estimated from the phase velocities of the materials anticipated at site:

$$\lambda = \frac{V_{PH}}{f}, \quad (1)$$

where f – the frequency, Hz; V_{PH} – phase wave velocity, m/s.

3. Methodology

3.1. Experimental set-up

In the FWD test, the road surface is applied with an impulsive load. The loading magnitude, duration and loading area are adjusted in a way that they correspond to the effect of loading due to standard axle vehicles on in-service pavement including the subgrade (Sebaaly *et al.* 1991; Ullidtz 1987). FWD could be used to determine the modulus of pavement material by using backcalculated stiffness obtained from its data (Salour *et al.* 2015). A schematic diagram of the FWD load and deflection measurement is presented in Fig. 1.

The instantaneous road surface deflections are measured at various point and lengths (0 to 1500 mm, and seven geophones used in this study), radiating outward from the centre of the falling weight. Therefore, the deflection bowl shape is obtained from the conducted test. Information on the subgrade can be taken from analysis (by back calculation, i.e. the ELMOD software) of the FWD data. It was found that the average elastic modulus and strain characteristic of subgrade are 148 MPa and 0.2765% respectively.

Meanwhile, Fig. 2a shows several impact source used to generate *R*-waves in the SASW test on a flexible pavement surface. In principle, the two accelerometers (Fig. 2b) are used to detect these waves, where the signals are recorded using an analogue digital recorder and a data acquisition system (notebook computer) for post processing (Fig. 2c). Several configurations of the source spacing and the

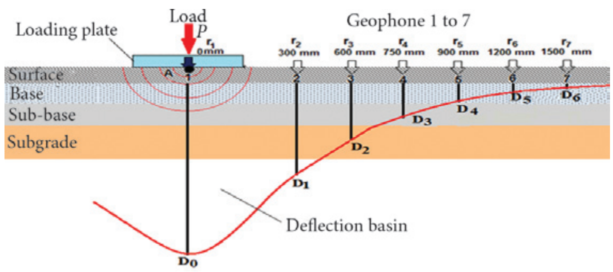

Fig. 1. Schematics of a FWD load and deflection measurement

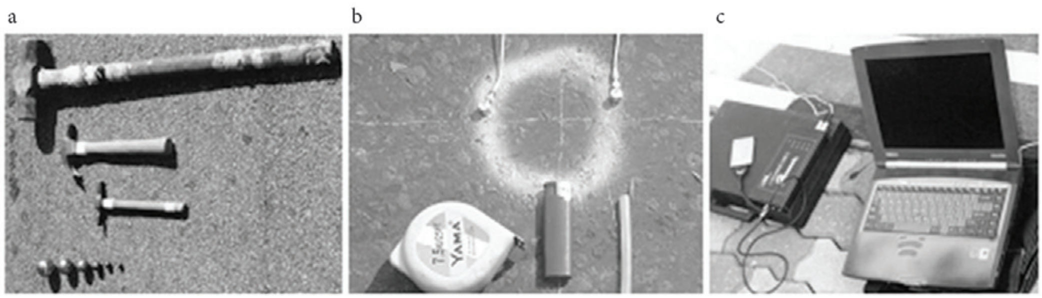

Fig. 2. Instruments used in SASW measurement: a – impact sources; b – accelerometers; c – spectrum analyzer

receiver are needed to acquire recorded signals at different depths. However, according to Heisey *et al.* (1982), the mid-point receiver spacing was found to be the best configuration in the SASW method (Fig. 3). For asphalt layer, the spacing between receivers is set to 4 and 8 cm. As this spacing is considered as short spacing, a high frequency source (ball bearing) is used for measurement. On the other hand, longer receiver spacing is needed to measure base and subgrade layer. The receiver spacing were set to 16, 32, 64 and 100 cm respectively and a set of ball-bearings and hammers were used as low frequency sources. Measurements were carried out using SASW method on existing flexible pavements along the Soekarno-Hatta Road and Cikampek-Purwakarta State (Province) Road in Indonesia, to a total of up to 45 locations altogether. Core-drilling result shows that the pavement profile of both roads has an asphalt mixture layer (150–200 mm), a crushed stone base course (150–200 mm) and a sub-base course (300–400 mm) overlaying a subgrade layer.

3.2. Data analyses procedure

In this research, measurement and inversion of dispersion curves and attenuation curves were done simultaneously. The coupled analysis developed for this paper is presented as flow diagram in Fig. 4. Further analysis procedure is elaborated in the following sub-topics.

3.2.1. Elastic modulus calculation

SASW measurements involve generating waves by impact source at one point on the pavement surface and recording them as they pass by two locations (receivers). In this study, accelerometers are used as receivers to record the signals of seismic energy in time domain. By applying the Fast Fourier Transform (FFT) to calculate the inverse Fourier transform, the Fourier transform procedure is used (Lu *et al.* 2014) and the signals recorded were later transformed to frequency domain and subsequently displayed in the transfer function spectrum. Determining transfer function (or frequency response spectrum) for a range of frequencies is required in order to determine the phase difference between two wave trains measured at two locations (channel 1 and channel 2). The wrapped phase angle calculated from a transfer function should be unwrapped for the calculation of phase velocities. Between the two receivers, the time lag is calculated by:

$$t(f) = \frac{\phi(f)}{(360f)}, \tag{2}$$

where $t(f)$ – the travel time, t; $\phi(f)$ – the phase angle difference at a given frequency, degrees.

Therefore, the Rayleigh wave velocity (V_R) or the phase velocity at a given frequency is obtained by:

$$V_R = \frac{d}{t(f)}, \tag{3}$$

where V_R – Rayleigh wave velocity, m/s; d – distance of receiver, m; $t(f)$ – time travel, t.

The corresponding wavelength of the Rayleigh wave, L_R, can be written as:

$$L_R(f) = \frac{V_R(f)}{f}, \tag{4}$$

where $L_R(f)$ – wavelength of Rayleigh wave, m; $V_R(f)$ – Rayleigh wave velocity, m/s; f – frequency, Hz.

Fig. 5 shows a typical phase plot of the transfer function for the measurement at a receiver spacing at the site of 100 cm. This spacing was set up to acquire seismic data in the subgrade layer. The frequency range of the data is around 180 to 1020 Hz, where the peak of the modulus plot for both signals in the transfer function spectrum is clearly observed.

The procedure outlined as above is repeated using Eq (2) through Eq (4) for each frequency to evaluate Rayleigh wave velocities in all range of wavelength and to

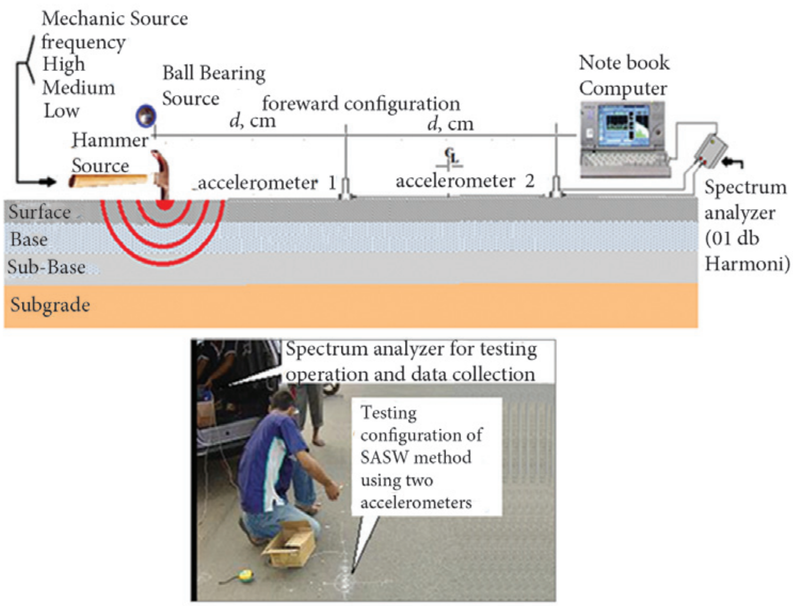

Fig. 3. SASW experimental set up

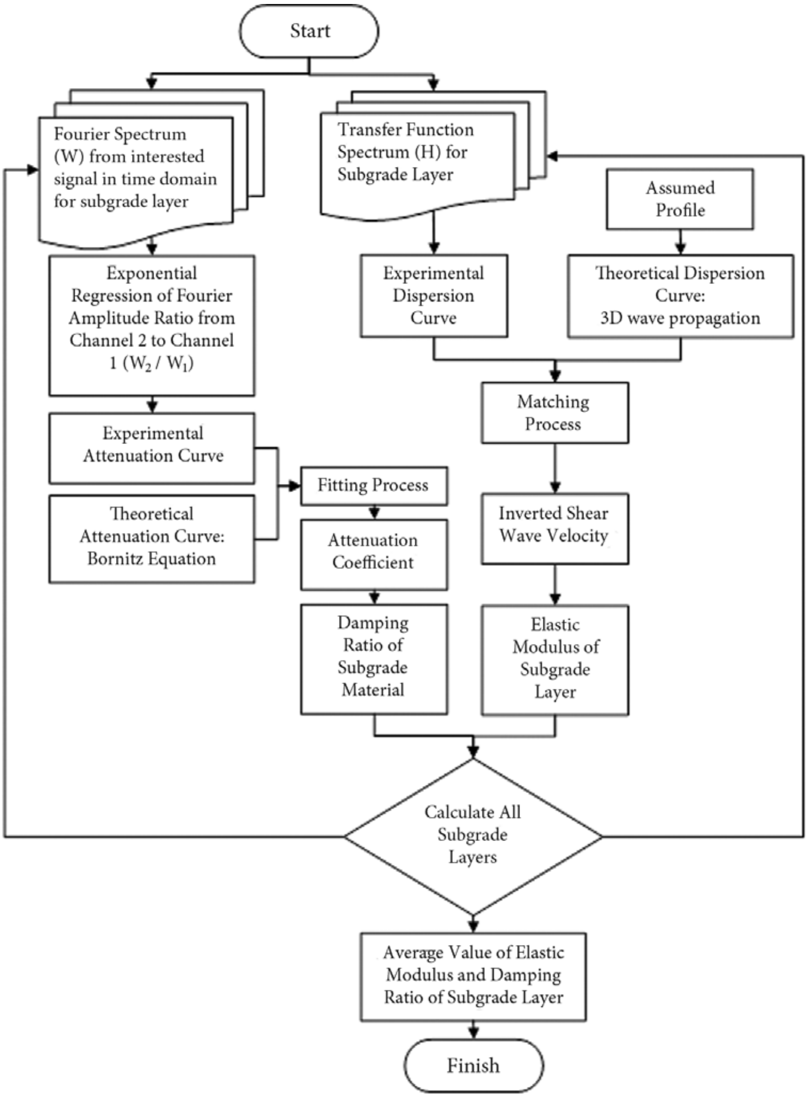

Fig. 4. Flow diagram of coupled analysis of the surface wave method

generate the experimental dispersion curve. An example of an experimental dispersion curve of the receiver spacings of interest for pavement structures is also shown in Fig. 5.

For complete evaluation of stiffness profile and to figure out the shear wave velocity profile of pavement, the experimental dispersion curve should undergo forward modelling analysis and inversion process. In forward modelling analysis, the initial layer properties should be provided to calculate the theoretical dispersion curve. There are many methods available to calculate dispersion curves of surface wave. This research employs the dynamic stiffness matrix method (Kausel, Röesset 1981). Theoretical dispersion curve is then compared to the experimental dispersion curve. Seismic inversion is the process of determining the physical characteristic of the seismic record that we viewed. For the formulation of the inversion problem, this research uses the maximum likelihood method as inversion procedure. The maximum likelihood method is defined as the most likely measurement with the highest probability (Joh 1996). Fig. 6 shows an example of a final theoretical dispersion curve with the best match to the experimental dispersion curve.

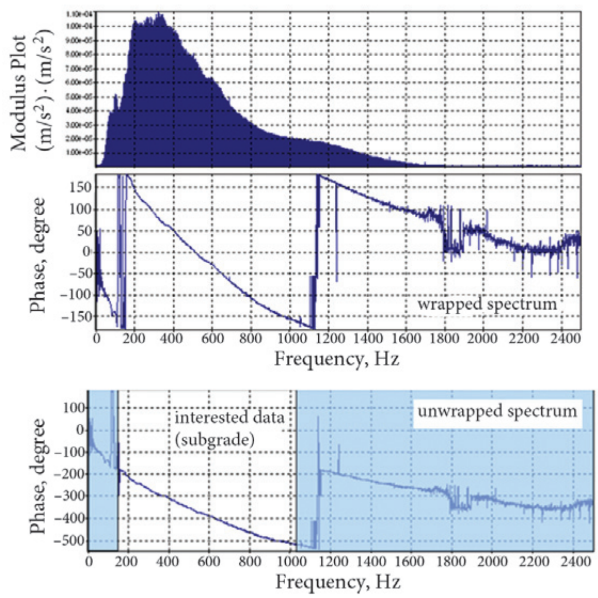

Fig. 5. Transfer function (dynamic modulus and phase information) obtained from measurement at 100 cm receiver spacing and its unwrapped phase spectrum with data of interest for the subgrade layer

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

$$E = 2\frac{\gamma}{g}V_s^2\left(1+\mu\right), \quad (5)$$

where g – the gravitational acceleration, m/s^2; γ – the total unit weight of the material, N/m^3; μ – the Poisson's ratio. Parameter of the modulus of a material is maximum at a strain below about 0.001% (Nazarian, Stokoe 1986). Therefore, the modulus is taken as a constant value in this strain range. The following parameter values are used in this study: μ = 0.33, ρ = 2000 kg/m^3 and g = 9.81 m/s^2.

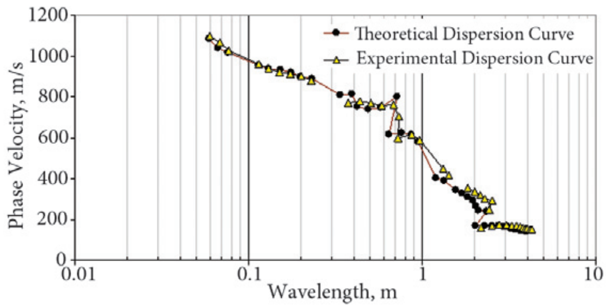

Fig. 6. A typical experimental dispersion curve from a complete set of SASW tests on the pavement model compared to a theoretical dispersion curve from 3D wave propagation theory, which shows the variation of wavelength with different phase velocities

Table 1. Attenuation radiation damping factor (n) with the source on the surface (Kim, Lee 1998)

Source type	Induced wave	n
Point	Body Wave	2.0
	Surface Wave	0.5
Infinite line	Body Wave	1.0
	Surface Wave	0.0

3.2.2. Attenuation and damping calculation

An effective damping ratio of the R-wave in a layered medium is frequency dependent. Its value can be very high for the first few vibration modes. The Bornitz Equation is the model used to explain a combination effect of both geometrical and material damping. This equation can be expressed as follows (Athanasopoulos *et al.* 2000):

$$w_2 = w_1\left(\frac{r_1}{r_2}\right)^n e^{-\alpha\left(r_1 - r_2\right)}, \quad (6)$$

where w_1 – the vibration amplitude at distance r_1 from the source, m; w_2 – the vibration amplitude at distance r_2 from the source, m; α – the attenuation coefficient of the material, m^{-1}; n – the attenuation factor (due to radiation damping), depending on the type of the induced seismic wave and its source (Table 1). The wave amplitude was attained from the Fourier spectrum by FFT analysis.

The α of the material depends on the type of the material and the vibration frequency. The estimated value of the α can be attained by means of the R-wave velocity (V_R), the vibration frequency (f) and the damping ratio (ξ), using Eq (7):

$$\alpha = \frac{2\pi f\xi}{V_R}, \quad (7)$$

where α – the attenuation coefficient of the material, m^{-1}; f – the vibration frequency, Hz; ξ – the damping ratio.

The aforementioned equation shows that the α linearly increases with the vibration frequency and is inversely proportional to the R-wave velocity.

According to Athanasopoulos *et al.* (2000), the frequency-independent attenuation coefficient can be alternatively obtained by re-arranging Eq (7):

$$\alpha_0 = \frac{\alpha}{f} = \frac{2\pi\xi}{V_R}, \quad (8)$$

where α_0 – the frequency-independent attenuation coefficient, s/m.

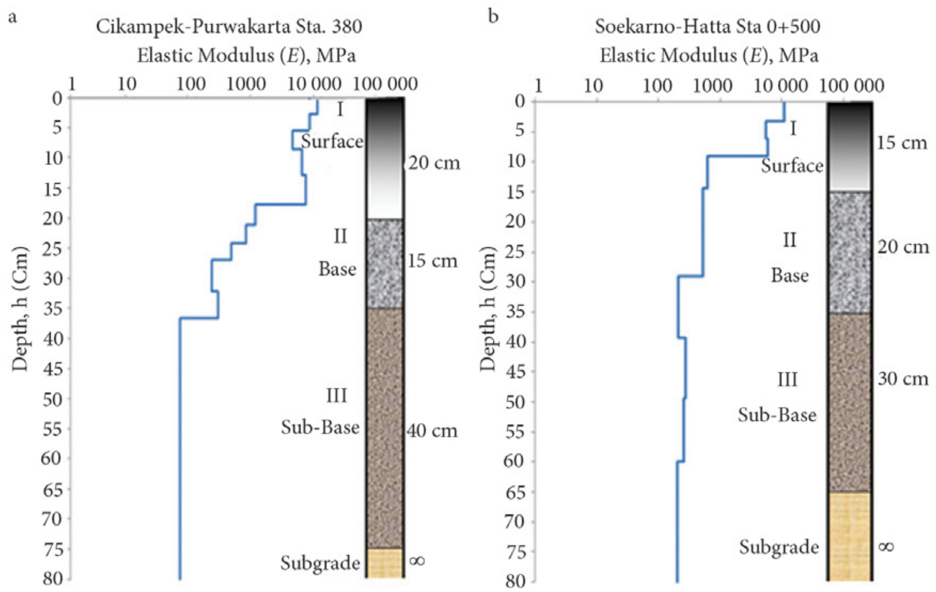

Fig. 7. The elastic modulus profile from the inverted-shear wave velocity profile for: a – Cikampek–Purwakarta State Road; b – Soekarno–Hatta State Road

4. Results and discussion

4.1. Elastic modulus of pavement subgrade

Fig. 7 shows the dynamic elastic modulus profile of pavements on both roads. The profile is obtained by implementing SASW method on the pavements studied using the dynamic material equation (Eq (5)). Compared to the profile obtained by core-drilling, the profile obtained by SASW method which employs 3D inversion analysis indicates each pavement layer clearly. The overlay and original layer were also well distinguished.

Fig. 8 shows the correlation of the elastic modulus of subgrade by SASW method and FWD test. Compared to result obtained by FWD test, the value of elastic modulus obtained by SASW method is higher. This occurred because the modulus measured at very low strain levels associated with the surface wave method is independent of strain amplitude and at its maximum value. The higher elastic modulus for subgrade obtained by SASW method is also due to the higher frequency used during measurement; compared to FWD test which measure the modulus at frequency of 30 Hz.

4.2. Attenuation of pavement subgrade

Attenuation of vibration is primarily caused by material damping and geometrical damping. Geometrical damping describes the spreading of wave energy while material damping describes the energy dissipation within soil particles. It has been shown that damping is dependent on excitation frequency (Connolly *et al.* 2014). In this study, the attenuation coefficient for the subgrade layer of pavement is determined by the SASW method. An example of the auto power spectrum for the first and second receiver at 100 cm receiver spacing is shown in Fig. 9.

Fig. 10 illustrates a general trend of frequency dependency curve. Based on the plot of ratio of second amplitude (w_2) over the first amplitude (w_1) against frequency, the decay factor curve of the *R*-wave for experimental data was determined. The experimental data was then used to obtain decay factor (dashed line) by applying a regression analysis. The Bornitz Equation could be expressed as:

$$\frac{w_2}{w_1} = 0.5^{0.5} e^{-\alpha_0 f}, \quad (9)$$

where w_1 – the vibration amplitude at distance r_1 from the source, m; w_2 – the vibration amplitude at distance r_2 from the source, m; α_0 – the frequency-independent attenuation coefficient, s/m; f – frequency, Hz.

Values of r_1 and r_2 are set to 1 and 2 m respectively for 100 cm receiver spacing. In Fig. 10, the decay factor of the experimental data is indicated in straight line while the theoretical curve of the Bornitz Equation is illustrated in black dotted line. The best-fit curve was then established between both of them by using a trial-and-error method for different values of α_0 from a visual best-fit evaluation of the two curves. It can be determined from Fig. 10 that the frequency-independent attenuation coefficient value is $2.04 \cdot 10^{-3}$ s/m for the pavement subgrade layer.

Table 2 lists the attenuation coefficient range of the pavement subgrade material obtained by means of the SASW method.

The frequency-independent attenuation coefficient values obtained were compared with the previous studies conducted by Yang (1995), Woods (1997) and Athanasopoulos *et al.* (2000). The results are shown in Fig. 11. It was

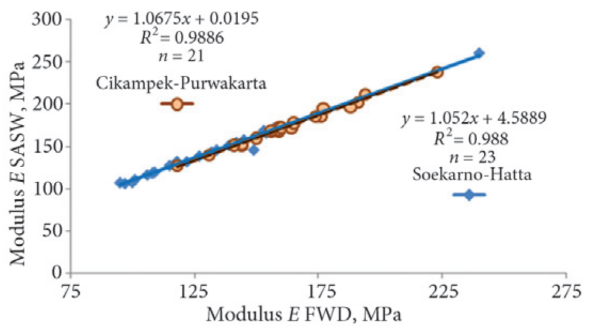

Fig. 8. Correlation of elastic modulus of subgrade by SASW method and FWD test for the Soekarno-Hatta and Cikampek-Purwakarta State Road

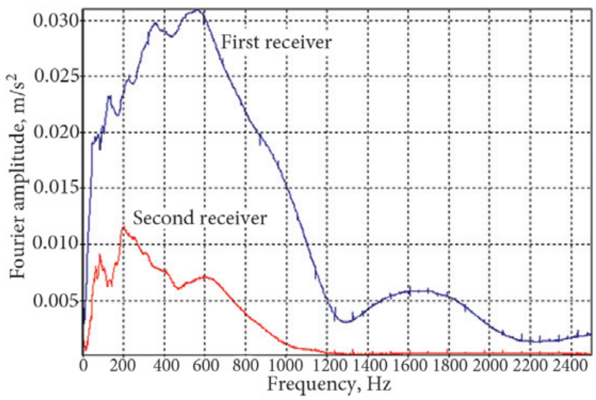

Fig. 9. Auto-power spectrum for the first and second receiver at 100 cm receiver spacing, measured at the Cikampek-Purwakarta State Road

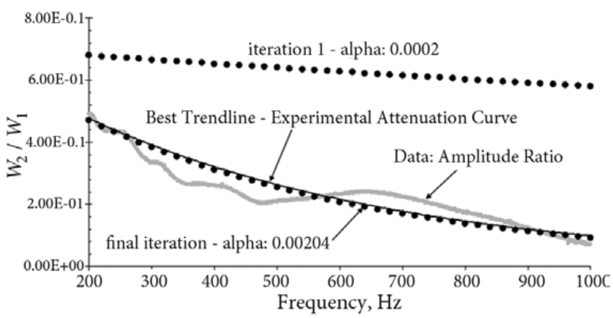

Fig. 10. The decay curve of the amplitude ratio (attenuation curve) versus frequency at 100 cm receiver spacing

Table 2. The averaged dynamic properties of pavement subgrade layers obtained from SASW measurement

V_S, m/s	*E*, MPa	Attenuation range 10^{-3}, 1/m	Damping ratio range, %
average 101	average 176	average 2.11	2.96–3.84

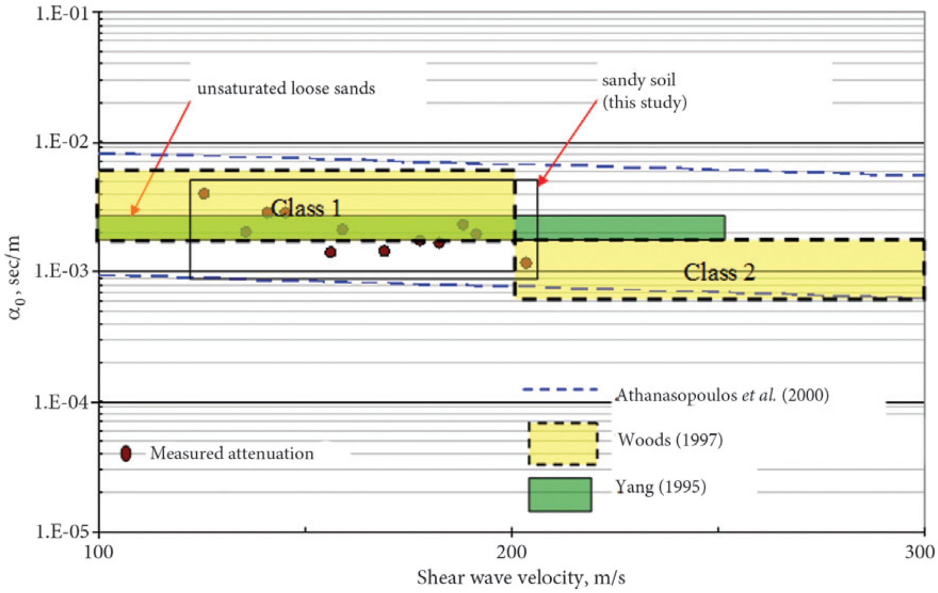

Fig. 11. A comparison of the frequency-independent attenuation factor versus shear wave velocity from this study and previous studies

observed that the attenuation coefficient values of the material for pavement subgrade are in the range of $1.15 \cdot 10^{-3}$ to $3.96 \cdot 10^{-3}$ s/m, with an average value of $2.11 \cdot 10^{-3}$ s/m. According to the Woods' classification (1997), these values fall into Class 1 and Class 2. It can be seen that for unsaturated loose sand material, the values of attenuation coefficient obtained in this study are higher than the study done by Yang (1995). This is most likely happened due to the difference in material. However, results obtained by the authors of this study fall well in within the upper bound and lower bound of the research conducted by Athanasopoulos *et al.* (2000).

Based on the shear wave velocity and the attenuation coefficient, Eq (7) was applied to obtain the damping ratio of the pavement materials. It is observed that the subgrade has damping ratio ranging from 2.96 to 3.84%, as presented in Table 2. At very low strain level (less than 0.001%) in which resulted by seismic measurement, the value of damping ratio is constant. On the other hand, experimental evidence shows that the damping ratio curve is affected by the strain rate at a higher strain level (Vucetic, Dobry 1991).

5. Conclusions

1. The correlation between the modulus from the Spectral Analysis of Surface Waves and the Falling Weight Deflectometer were found to be significant with $R^2 > 0.98$.

2. A coupled analysis of the elastic modulus and damping ratio for the pavement subgrade layer using the Spectral Analysis of Surface Waves method is discussed. Due to the small strain levels and high frequency involved in the measurements, the values of elastic modulus of the subgrade material are relatively higher compared to the modulus obtained from Falling Weight Deflectometer measurements.

3. The attenuation coefficients obtained in this study and the previous research matched pretty well.

4. The spectral analysis of surface wave method, therefore, is able to characterise in-situ stiffness in terms of elastic modulus, shear wave velocity and the damping ratio for the pavement subgrade structure.

Acknowledgments

The authors express their gratitude to Universitas Muhammadiyah Yogyakarta and Universiti Kebangsaan Malaysia (DLP-2013-028) for the support of this work. This research was also partly supported by Puslitbang Jalan dan Jambatan, Bandung, Indonesia.

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Received 20 August 2012; accepted 28 September 2012