Experimental Investigation of Seismic Parameters and Bearing Capacity of Pavement Subgrade Using Surface Wave Method

(Investigasi Eksperimen Parameter Seismik dan Daya Dukung Tanah Dasar Perkerasan Menggunakan Metode Gelombang Permukaan)

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ABSTRACT

The spectral analysis of surface waves (SASW) method is introduced as an in-situ non-destructive seismic technique where the method consists of the generation, measurement and processing the dispersive Rayleigh waves from two vertical transducers. Subsequently, the dispersive data of Rayleigh phase velocity are inverted and the shear wave velocity versus depth of the site is obtained. The dynamic stiffness parameters, i.e. elastic modulus generated from the SASW measurements are at a very small strain levels of < 0.001%. At this strain level the soil is linearly elastic and the use of elastic theories is thus justified. The aim of this paper is to investigate the seismic parameters of the pavement subgrade stiffness using the SASW method and to predict its bearing capacity based on the seismic parameters. In order to determine the bearing capacity, in situ dynamic cone penetrometer (DCP) was also carried out in the same location of SASW test. The relationship of the shear wave velocity and dynamic elastic modulus ($E_{dynamic}$) of the SASW were found to be in good correlation with bearing capacity obtained by the DCP.

Keywords: method, soil stiffness, bearing capacity, shear wave velocity, elastic modulus

INTRODUCTION

One of important features in a pavement management system is its ability to determine the current and predict the future condition of the pavement subgrade. For assessing the structural capacity of the subgrade layer, accurate information of the elastic moduli and thicknesses of the soil material is needed. Generally, those parameters are used to calculate the load capacity and to estimate the surface deflection under the center of a tire loading in order to predict the performance of pavement structure. The performance of pavement structures is mostly affected by the soil bearing capacity of the subgrade layer. In pavement construction, the soil test of dynamic cone penetrometer (DCP) is a common tool for measurement the soil stiffness of pavement subgrade layer. It is a simple test device that is inexpensive, portable, easy to operate, and easy to understand. It does not take extensive experience to interpret results and several correlations to more widely known strength measurements have been published (Burnham & Johnson, 1993). The DCP quickly generates a continuous profile of in situ subgrade measurements.

However, the need for accurate, cost-effective, fast and a non-destructive testing (NDT) of soil stiffness system is becoming ever important because the rehabilitation and management of roads is becoming increasingly difficult for the increasing number of aging roads and limited budgets. The DCP test and other destructive testing are not effective anymore for this purpose. The spectral analysis of surface waves (SASW) is an NDT method based on the dispersion of Rayleigh waves (R waves) to determine the shear wave velocity, modulus and depth of each layer of the pavement profile (Nazarian & Stokoe, 1986). 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. These applications include detection of soil profile, evaluation of concrete structures, detection of anomalies, detection of the structural layer of cement mortar, assessing compaction of fills and the evaluation of railway ballast. The purpose of this paper is to investigate the seismic parameters of soil dynamic and its relationship to the empirical bearing capacity (corresponding to DCP value) of the pavement subgrade using the Spectral Analysis of Surface Wave (SASW) method. Two national and state (province) roads in Yogyakarta, Indonesia are chosen as a case in this study.

EXPERIMENTAL SETUP

Field Measurement

An impact source on a pavement surface is used to generate *R* waves. These waves are detected using two accelerometers of piezoelectric DJB A/123/E model (Figure 1) where the signals are recorded using an analog digital recorder of Harmonie 01 dB (IEC 651-804 Type-I) and a notebook computer for post processing (Figure 2). Several configurations of the receiver and the source spacings are required in order to sample different depths (Figure 3). The best configuration is the midpoint receiver spacings (Heisey et al.,1982). The range of wavelength to be used as a guide for the receiver spacing can be estimated from the shear wave velocities of the material anticipated at the site:

$$\lambda = \frac{V_s}{f} \tag{1}$$

where f is the frequency and V_S is shear wave velocity. The higher and low frequency wave groups needed can be generated by various transient sources of different weights and shapes (Rosyidi et al., 2002, Rosyidi, 2004, 2009).

In this study, the short receiver spacings of 4 and 8 cm with a high frequency source (ball bearing) are used to sample the asphaltic layers while the long receiver spacings of 16, 32 cm and 64, 100, 200 cm with a set of low frequencies sources (a set of hammers) are used to sample the base and subgrade layers, respectively (Figure 4). The SASW tests were carried out at two locations on Wonosari National Road (Piyungan to Gading) and Prambanan State Road (Prambanan to Pakem), Yogyakarta Province, Indonesia which 20 SASW measurements were conducted for each location.

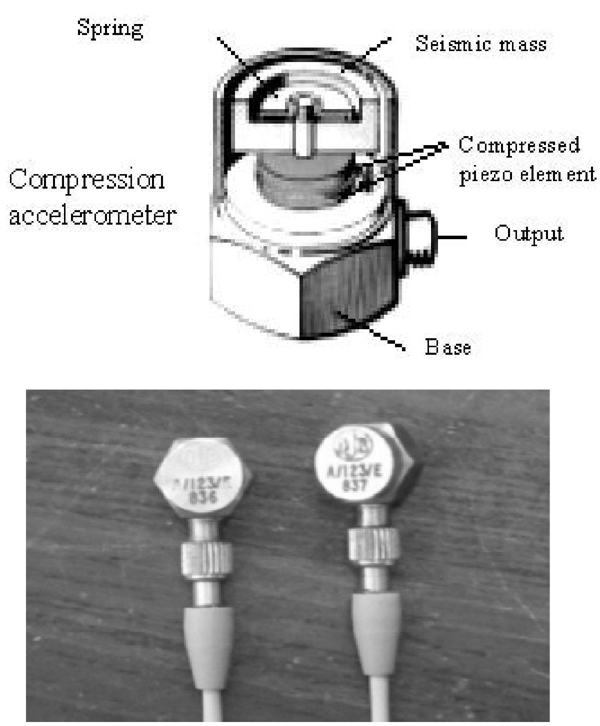


FIGURE 1. Accelerometer used in test

FIGURE 2. Unit acquisition of SASW test

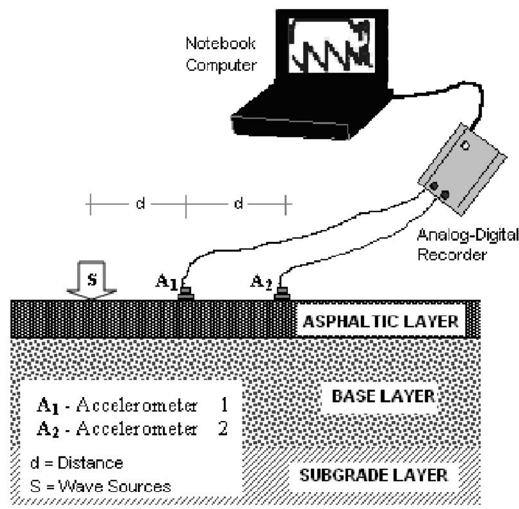


FIGURE 3. SASW experimental set up

SUMBER: Rosyidi et al. (2005)

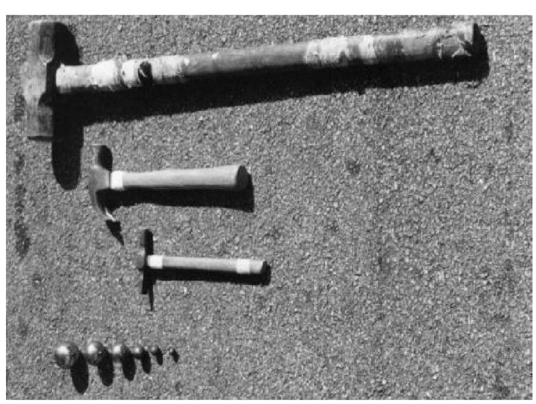


FIGURE 4. Various sources used in tests

Data Analysis

1. Experimental dispersion curve

All the data collected from the recorder are transformed using the Fast Fourier Transform (FFT) to frequency domain by the dBFA32 software resident in the notebook computer. The phase spectrum in the frequency domain between the two receivers is of great importance in the data analysis. The phase data can be obtained from the cross-power spectrum or the transfer function spectrum. The spectrum consists of the relative phase shift between the two signals in the range of the frequencies being generated. However, in fact, during data collection, some noisy signals may interrupt the seismic data. It causes the phase spectrum pattern cannot be smooth looking. Figure 5 shows a typical set of the phase spectrum of the transfer function from the measurement from 4, 64 and 200 cm receiver spacings at the site. From Figure 5, it is shown that the phase spectrum for 4 cm spacing is in good quality graph where the phase shift data between two sensors are not interrupted by noisy signals. However, for 64 and 200 cm, the noisy signals which is recognized as low frequency incoherent noisy interrupted to the phase data in the spectrum.

The experimental dispersion curve of phase velocity and wavelength is then developed from phase information of the unwrapped transfer function at the selected frequency range. In addition, most of researchers apply the filtering criteria (Heisey et al., 1982) with a wavelength greater than ½ and less than 3 receiver spacings. The time of travel between the receivers for each frequency can be calculated by:

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

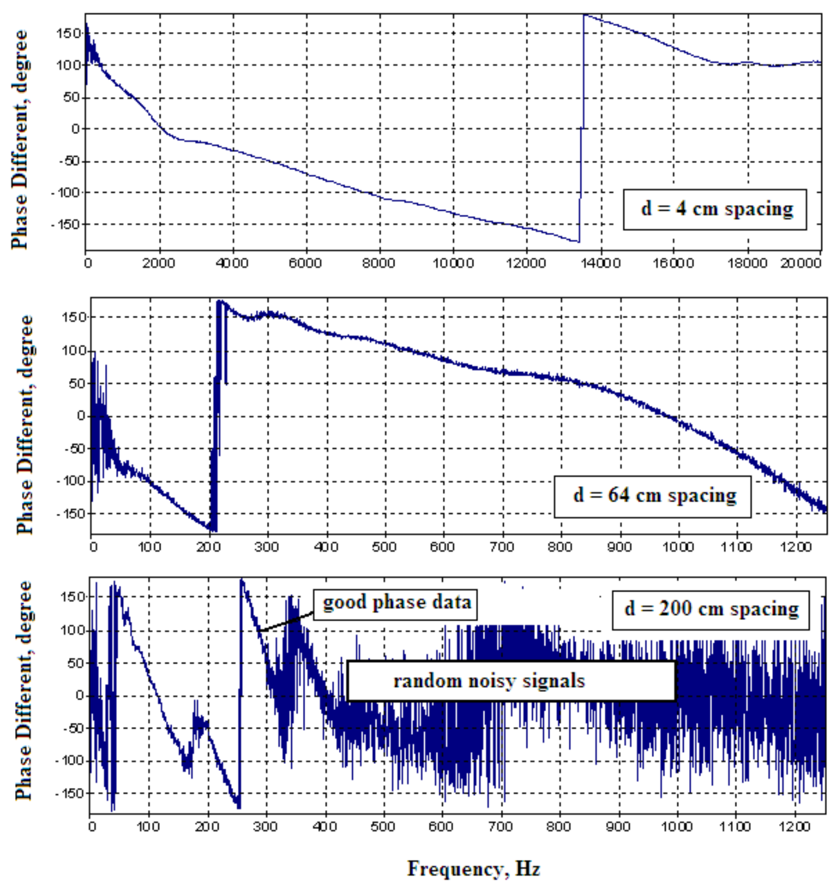


FIGURE 5. Phase spectrum of transfer function for 4, 64 and 200 cm

where f is the frequency, $t(f)$ 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, R wave velocity, VR or the phase velocity at a given frequency is simply obtained by:

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

and the corresponding wavelength, L_R may be written as:

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

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. Figure 6 shows an example of the composite experimental dispersion curve from measurements of all the receiver spacings for Pakem-Prambanan and Wonosari road.

2. *Inversion analysis*

The actual shear wave velocity of the pavement profile is produced from the inversion of the composite experimental dispersion curve. In inversion process, a profile of a set 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 modeling analysis of the 3 D dynamic stiffness matrix method (Kausel & Röesset, 1981). The theoretical dispersion curve is ultimately matched to the experimental dispersion curve of the lowest RMS error with an optimization technique called the "Maximum Likelihood Method" (Joh, 1996). Finally, the profile from the best-fitting (lowest RMS) of the theoretical dispersion curve to the experimental dispersion curve is used that represents the most likely pavement profile of the site. Detail procedure and equations used in SASW inversion analysis using the 3-D stiffness matrix was discussed in Rosyidi (2007). Figure 7 presents the example of final shear wave velocity profile obtained from the SASW measurement on the Prambanan-Pakem road. The final profile was generated from the best-fitting between the theoretical and experimental dispersion curve which the value of RMS error is found to be 25.37 m/s.

The dynamic elastic modulus of the pavement materials can then be easily determined from the following equation (Yoder &Witczak, 1975):

$$E = 2\frac{\gamma}{g}V_S^2(1+\mu) \tag{5}$$

where g is the gravitational acceleration, γ is the total unit weight of the material and μ is the Poisson's ratio.

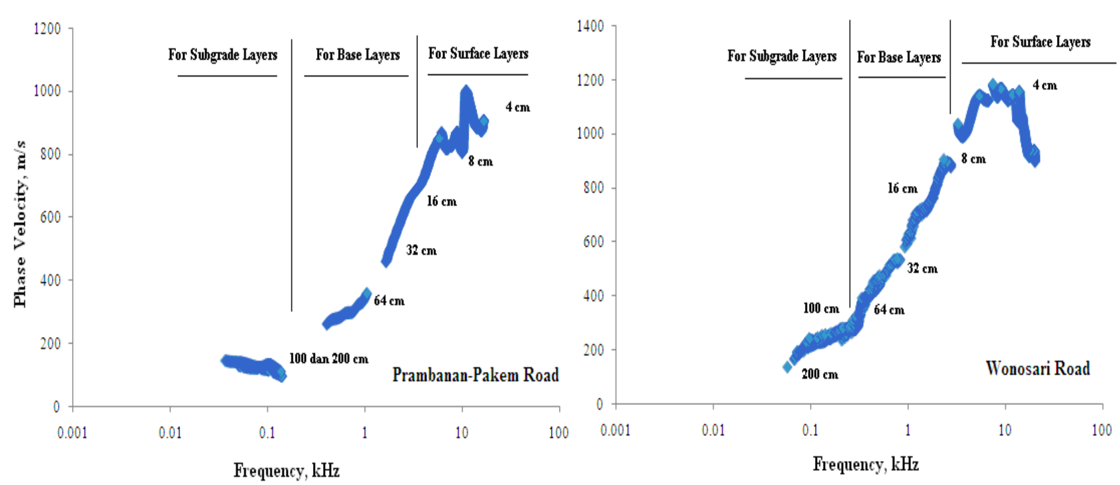


FIGURE 6. A typical dispersion curve from a complete set of SASW tests on the flexible pavement showing the variation of wavelength with different layers of its profile on Prambanan-Pakem and Wonosari road

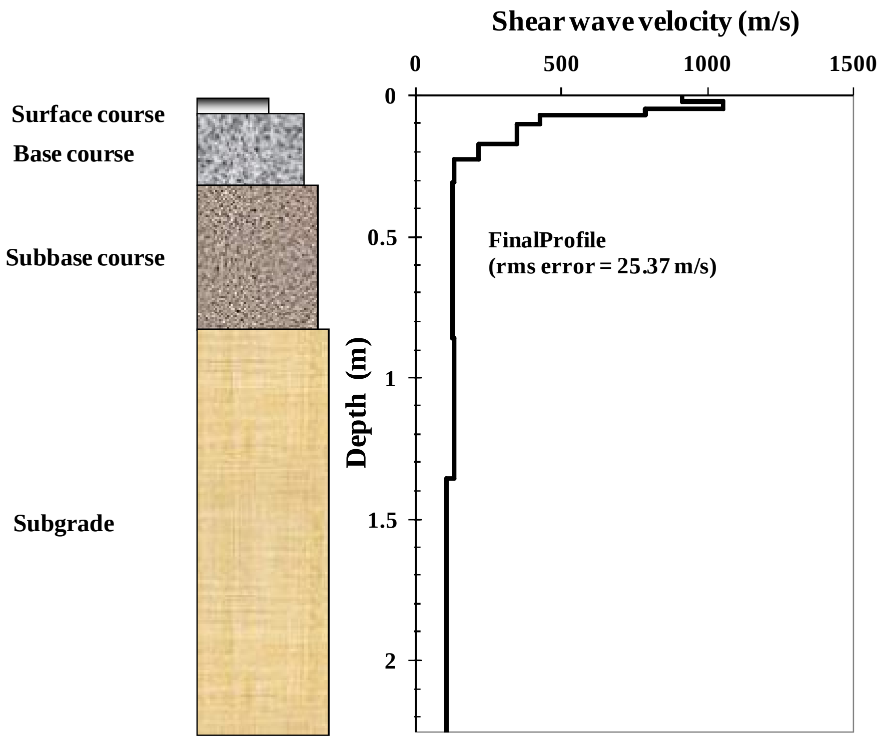


FIGURE 7. Final shear wave velocity profile of Prambanan-Pakem road-pavement from the SASW measurement

Nazarian and Stokoe (1986) 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. Figure 8 shows an example of the elastic modulus profile of Prambanan-Pakem road-pavement which is obtained from the shear wave velocity profile (Figure 7). The total unit weight of each pavement layer and Poisson's ratio were assumed in reasonable values.

Dynamic Cone Penetrometer (DCP)

The DCP tests were conducted for determining the soil bearing capacity of the pavement subgrade on the same SASW measured centre points. The DCP uses a 8 kg steel mass falling 20 inches (50.8 cm) striking an anvil causing a penetration of 1.5 inches (3.8 cm) from a cone with a 60° vertex angle seated in the bottom of a hand augered hole. The blows required to drive the embedded cone a depth of 1-3/4 inches have been correlated to N values of the Standard Penetration Test (SPT). The DCP can be used effectively in augered holes to depths of 15 to 20 ft. (4.6 to 6.1 m). The depth of cone penetration is measured at selected penetration or hammer-drop intervals, and the soil shear strength is reported in terms of DCP index. The DCP index (mm/blows) is based on the average penetration depth resulting from one blow of the 8 kg hammer. The readings of DCP are taken directly from the graduated steel rule attached to the instrument.

RESULTS AND DISCUSSION

From the 3-D forward modeling using the stiffness matrix method (Kausel & Röesset 1981), the average inverted shear wave velocities for subgrade layer from Wonosari Road at 10 measured points is 284.77 m/s with a range of 111.7 to 355.89 m/s. For Wonosari Road, the average value of shear wave velocity is 212.42 m/s with a range of 101.6 to 295.2 m/s for the compacted subgrade layer. The average value of dynamic elastic modulus calculated from Equations 5 of subgrade material is listed in Table 1. The average value of elastic modulus (in MPa) from each point at test sites is shown in Figure 7 (Wonosari Road) and Figure 8 (Prambanan Road).

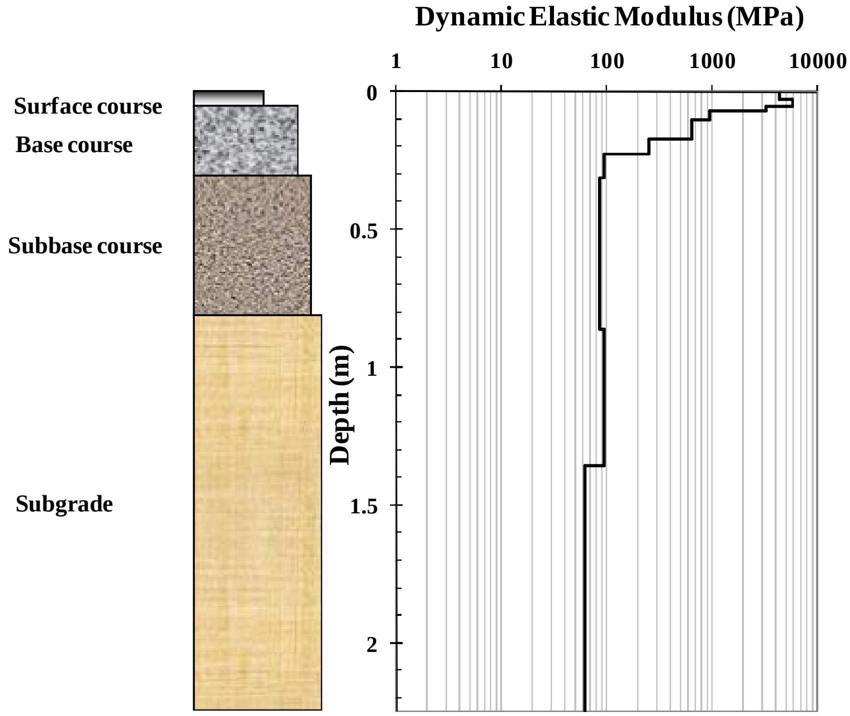
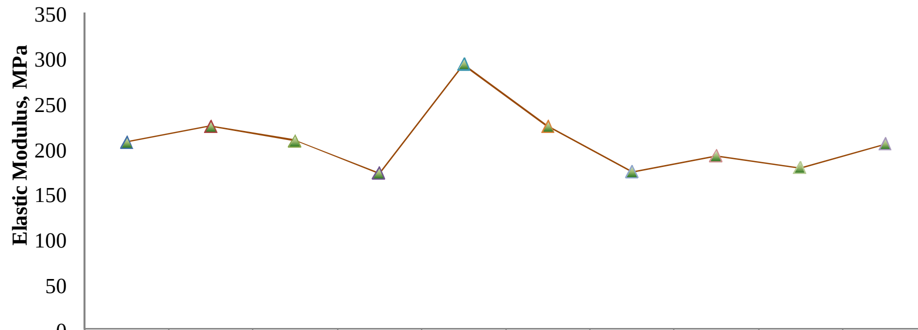


FIGURE 8. Final elastic modulus profile of Prambanan-Pakem road-pavement from the SASW measurement

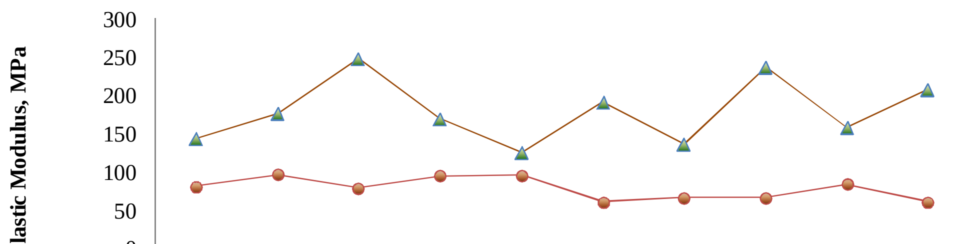
TABLE 1. The average dynamic elastic and shear modulus of the subgrade layer

Subgrade Pavement Layer	Dynamic Properties	
	Wonosari Road	Prambanan Road
Dynamic Stiffness		
Average Shear Wave Velocity (m/s)	284.77	212.42
Average Elastic Modulus, E (MPa)	208.46	180.64 (subgrade) 75.17 (natural soil)
Range of E (MPa)	111.7 – 355.89	101.6 – 295.2 (subgrade) 30.7 – 99.6 (natural soil)
CV of E	0.31	0.33 (subgrade) 0.25 (natural soil)
SD of E (MPa)	64.55	59.58 (subgrade) 18.76 (natural soil)
Soil Subgrade Classification	Poorly Graded *Keprus* chalky limestone	Poorly Graded Clayey Sandy Soil



	1	2	3	4	5	6	7	8	9	10
Subgrade layer	207.710	224.919	209.181	173.055	293.802	224.785	174.537	192.251	179.012	205.326

FIGURE 7. Average dynamic elastic modulus of pavement profiles at Wonosari Road



	1	2	3	4	5	6	7	8	9	10
Subgrade layer	141.576	175.026	246.712	167.357	123.571	189.800	134.442	235.701	156.939	206.484
natural soil layer	80.207	95.649	77.680	93.257	94.815	59.356	64.154	65.039	82.381	59.2630

FIGURE 8. Average dynamic elastic modulus of pavement profiles at Prambanan Road

The shear wave velocities and their corresponding shear modulus from this study are listed in Table 2 in comparison with the results of SASW testing obtained by other researcher (Nazarian & Stokoe, 1986). In general, the shear wave velocity values of the subgrade at Wonosari and Prambanan-road are in reasonable agreement with the result of a chalky lime stone and loose sandy soil subgrade layer from the study obtained by Anderson and Thitimakorn (2004), and Nazarian and Stokoe (1986), respectively which is described in Table 2.

The shear wave velocities from the SASW are then correlated to the DCP value for the evaluation of the bearing capacities of the subgrade materials. The empirical model between the shear wave velocities and DCP values can also be employed for the subgrade layer using empirical models proposed by Rosyidi (2004) which were written as:

$$DCP = 45{,}668\ (V_S)^{-1.58} \qquad (7)$$

$$DCP = 709.18(E_{SASW})^{-0.79} \qquad (8)$$

where, V_S = shear wave velocity (m/s) and DCP is the penetration per mm of a 8 kg drop weight.

The trend of empirical model is shown in Figure 9. Figure 9 also shows that the increased in the shear wave velocities correlates well with the DCP values. The coefficients of determination obtained (Figure 9) indicate that the empirical equation derived between the shear wave velocities have significant correlations with the DCP. The average values of the DCP index of the pavement subgrade at each of the SASW measurement point can be calculated as shown in Figure 10. The result shows that the soil bearing capacity which is represented by the DCP index can be obtained from the seismic parameter (shear wave velocity and corresponding to the dynamic elastic modulus) using the SASW method.

TABLE 2. Comparison of shear wave velocity on subgrade layers

Parameter	This study	Other Studies
Shear wave velocity, V_S (m/s)	Wonosari road: 111.7 – 355.89 m/s (*keprus* chalky limestone) Prambanan road: 101.6 – 295.2 (subgrade: dense sandy soil) 30.7 – 99.6 (loose sandy soil)	Anderson & Thitimakorn (2004): > 280.42 m/s (limestone) Nazarian & Stokoe (1986): 147.5 – 211.9 m/s (sandy soil)

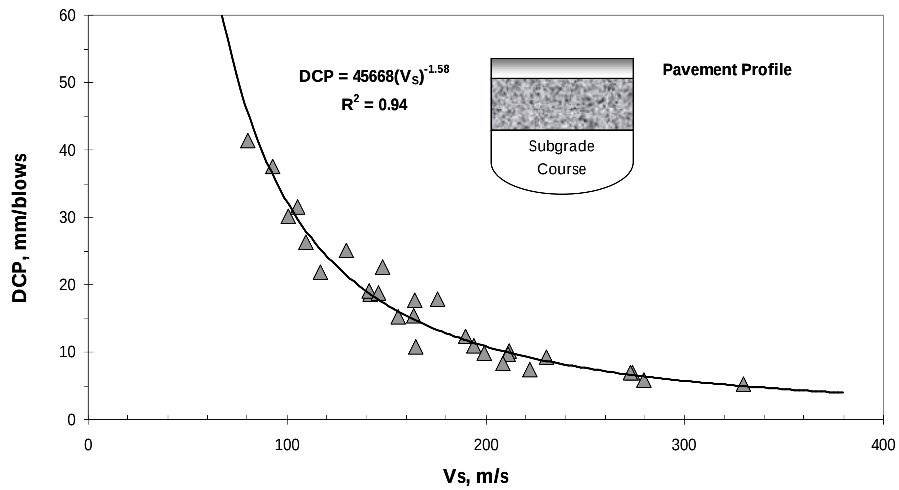
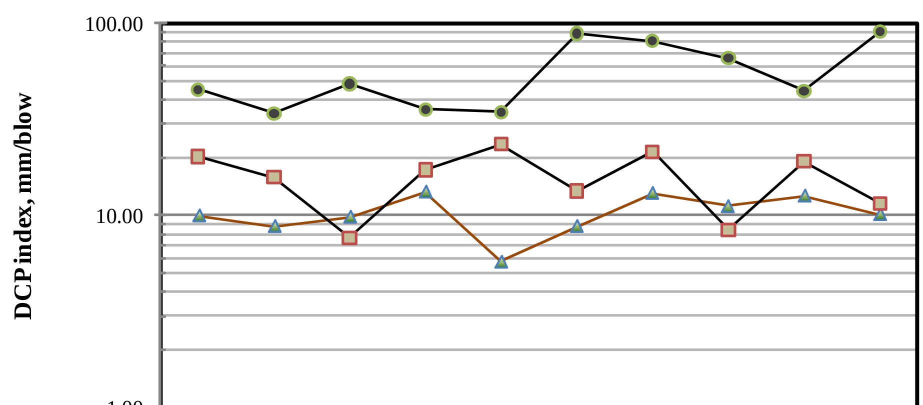


FIGURE 9. Correlation between the shear wave velocity and DCP for the subgrade layer



	1	2	3	4	5	6	7	8	9	10
Wonosari Road	9.95	8.78	9.84	13.28	5.76	8.79	13.10	11.25	12.59	10.14
Prambanan Road (subgrade)	20.212	15.769	7.710	17.270	23.366	13.423	21.431	8.447	19.032	11.593817
Prambanan Road (natural soil)	45.174	33.937	48.307	35.338	34.387	88.129	80.792	65.455	44.227	89.912777

FIGURE 10. Average bearing capacity calculated from empirical model of elastic modulus versus the DCP index proposed by Rosyidi (2004) for Wonosari and Prambanan Road

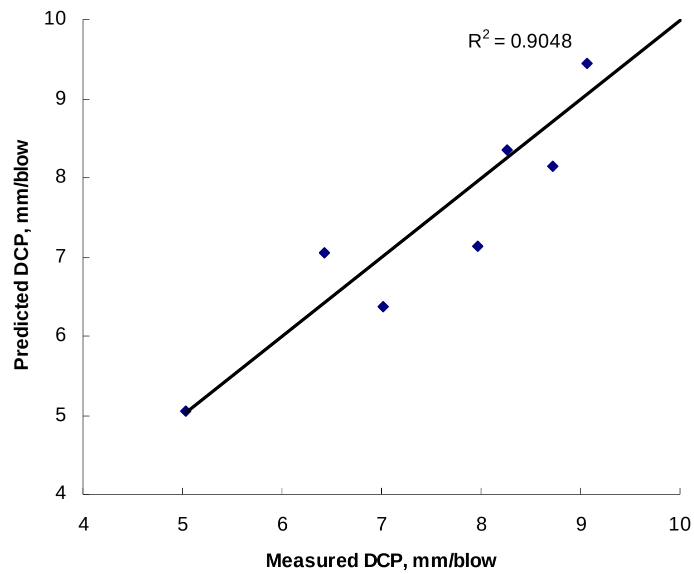


FIGURE 11. Comparison between DCP values from predicted DCP from Rosyidi's (2004) empirical equations and field measurement at Prambanan Road

For validate the derived equation in this study, Figure 11 also shows a correlation between the predicted DCP values using Equation 7 from SASW measurement and the DCP values from the field measurement at several locations on State Road, Prambanan – Pakem, Indonesia. The result is in good agreement with determination coefficient, $R^2 = 0.91$.

CONCLUSIONS

Good agreements were obtained between the measured shear wave velocities and the corresponding dynamic elastic of the soil subgrade from this study as compared to other works. This study has also investigated to the soil bearing capacity obtained by seismic parameter based on Rosyidi's (2004) empirical model. An excellent correlation between the shear wave velocity and the DCP index measured for subgrade layers was obtained from this study. Based on this experimental study, it can be concluded that the SASW method is able to predict the soil stiffness of the pavement subgrade layer in terms of shear wave velocity and its corresponding dynamic elastic modulus satisfactorily for the propose of pavement evaluation.

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