Investigation of seismic parameters and bearing capacity of pavement subgrade

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ABSTRACT

The Dynamic Cone Penetrometer (DCP) is a test device used for measuring the strength and variability of unbound layers of soil and granular material. From an operational perspective the DCP is very attractive because the DCP is both portable and simple to use. However, the method is time consuming, destructive and is costly. 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 waves 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 obtain the empirical equation in order to predict the soil stiffness of pavement subgrade using the SASW method. In situ dynamic cone penetrometer (DCP) was also carried out in the same location of SASW test. The DCP results showed the 8 kg hammer blows per penetration depth corresponding to soil strength of subgrade layer. The relationship of the shear wave velocity and dynamic elastic modulus ($E_{dynamic}$) of the SASW were found to be in good correlation with the DCP.

Keywords: *SASW Method, Soil Stiffness, Shear Wave Velocity, Dynamic Elastic Modulus*

1. INTRODUCTION

An important feature of a pavement management system is its ability to determine the current and predict the future condition of the pavement. In order to establish the structural capacity of the existing roads, accurate information of the elastic moduli and thicknesses of the various pavement layers are needed. 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, select and design appropriate rehabilitation techniques. The performance of pavement structures is most affected by the soil bearing capacity of the subgrade layer and commonly called the soil stiffness parameter. The Dynamic Cone Penetrometer (DCP) is one of tools 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 for the increasing number of aging roads and limited budgets. 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 obtain the empirical equation in order to predict the soil stiffness (corresponding to DCP value) of the pavement subgrade system using the Spectral Analysis of Surface Wave (SASW).

2. LITERATURE REVIEW

2.1 The spectral analysis of surface waves

The SASW method is based on particles motion of R wave in heterogeneous media. The energy of R waves from the source propagates mechanically along the surface of media and their amplitude decrease rapidly with depth. Particle motions associated with R wave are composed of both vertical and horizontal components, which when combined formed a retrogressive ellipse close to the surface. In homogenous, isotropic, elastic half-space, R wave velocity does not vary with frequency. However, R wave velocity varies with frequency in layered medium where there is a variation of stiffness with depth. This phenomenon is termed dispersion where the frequency is dependent on R wave velocity. The ability to detect and evaluate the depth of the medium is influenced by the wavelength and the frequency generated. 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 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).

The experimental dispersion curve of phase velocity and wavelength may be developed from phase information of the transfer function at the frequency range satisfying the coherence criterion. 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:

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

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, V_R or the phase velocity at a given frequency is simply obtained by:

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

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

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

The actual shear wave velocity of the pavement profile is produced from the inversion of the composite experimental dispersion curve. In the 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.

2.2 The dynamic cone penetrometer (DCP)

The dynamic cone penetrometer (DCP) is used as a rapid means of assessing the sequence, thickness and the in-situ bearing capacity of the unbound layers and the underlying subgrade of the pavement structure. 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.

3. RESEARCH METHODS

3.1 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 mid point receiver spacings (Heisey et al.,1982).

In this study, the short receiver spacings of 5 and 10 cm with a high frequency source (ball bearing) are used to sample the asphaltic 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) are used to sample the base and subgrade layers, respectively (Figure 4). The SASW tests were carried out at two location which 20 sites on National Road, Piyungan to Gading and State Road, Prambanan to Pakem, Yogyakarta Province, Indonesia. Data were collected together with the DCP tests conducted on the same SASW measured centre points.

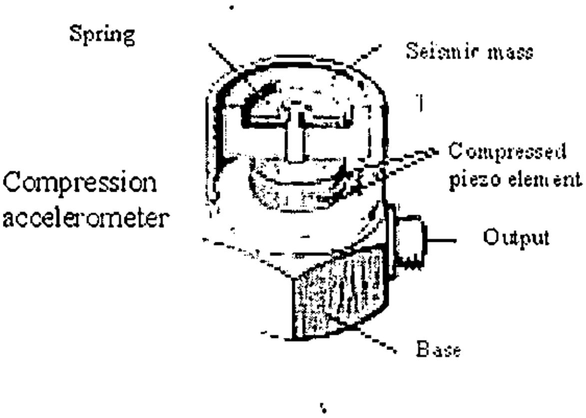

Figure 1. Accelerometer used in test

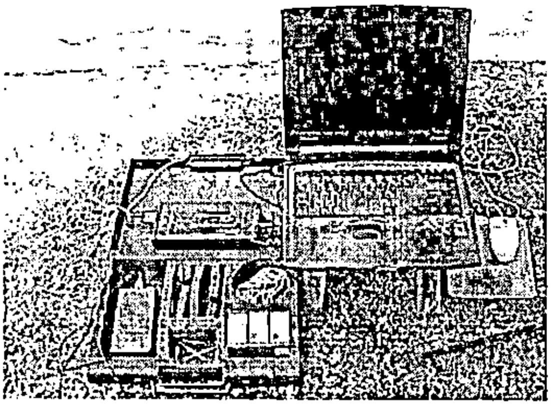

Figure 2. Unit acquisition of SASW test

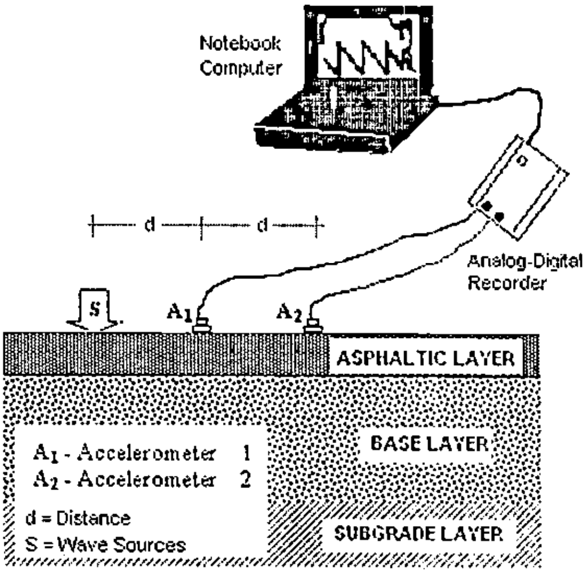

Figure 3. SASW experimental set up

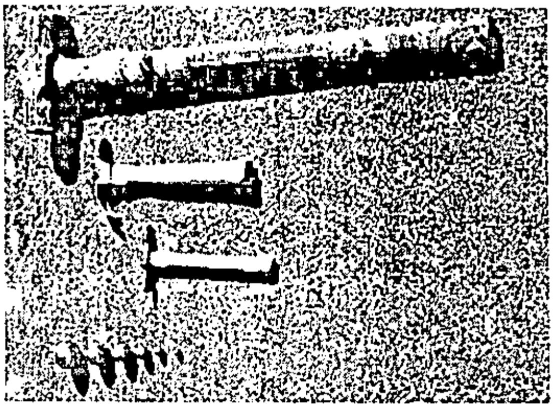

Figure 4. Various sources used in tests

3.2 Data Analysis

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. Two functions in the frequency domain between the two receivers are of great importance: (1) the coherence function, and (2) the phase information of the transfer function. 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 transfer function spectrum is used to obtain the relative phase shift between the two signals in the range of the frequencies being generated.

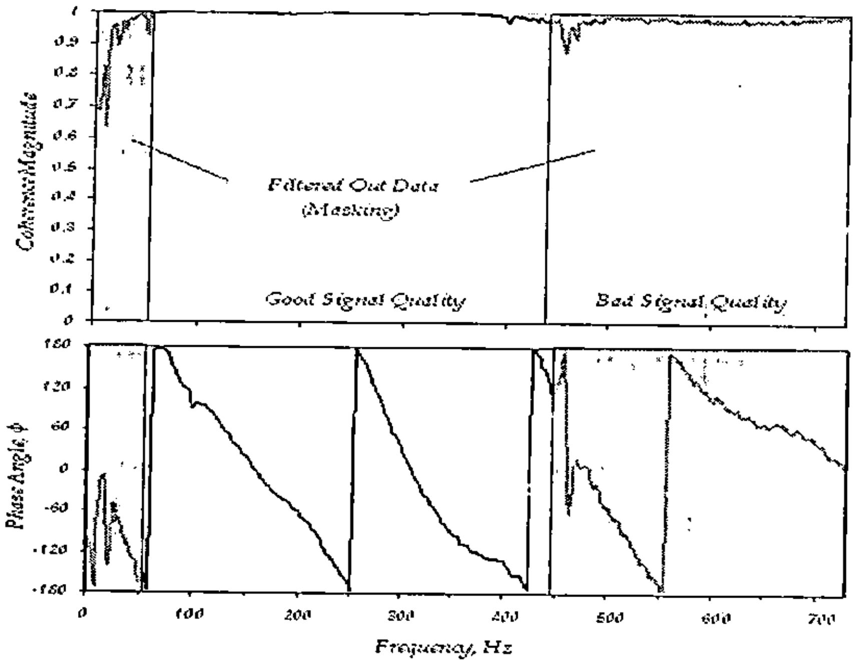

Figure 5. The coherence and the transfer function spectrum for an 80 cm receiver spacing

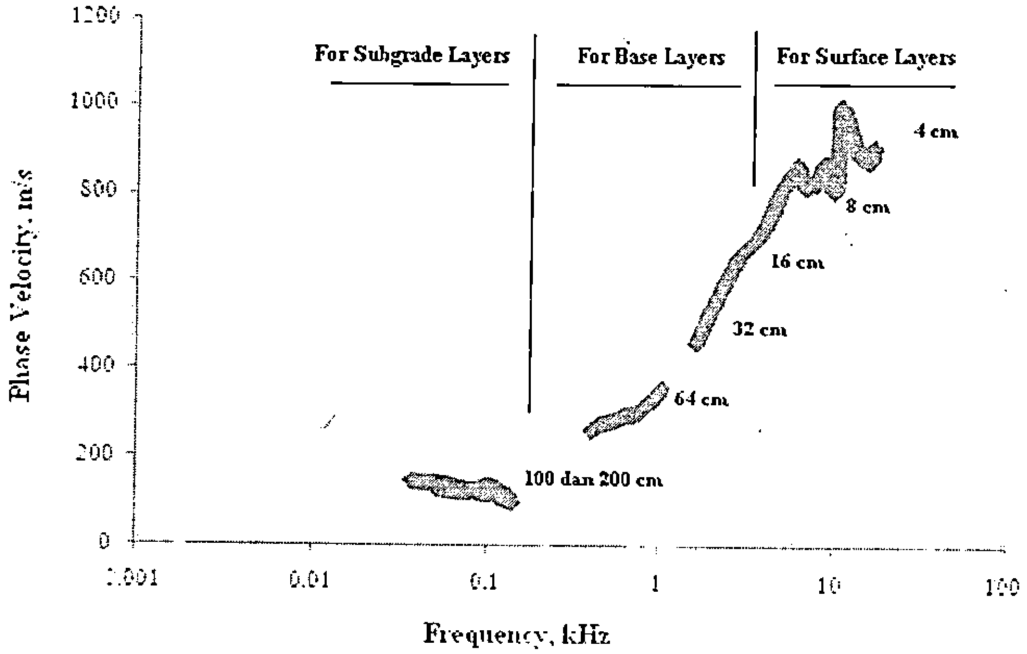

Figure 6. A typical dispersion curve from a complete set of SASW tests on the flexible pavement showing the variation of wavelength with different layers of

Figure 5 shows a typical set of the coherence and the phase plot of the transfer function from the measurement of an 80 cm receiver spacing at the site. 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 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.

4. RESULT 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 the first location (Prambanan-Pakem Road) at 10 measured points is 212.42 m/s is with a range 162.69 to 353.06 m/s. The average value of dynamic elastic and shear modulus calculated from Equations 5 and 6 of subgrade material and the property of soil subgrade are listed in Table 1. The average value of shear wave velocity (in m/s), elastic and shear modulus (in MPa) from each point at test sites are shown in Figure 7.

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

Subgrade Pavement Layer	Properties
	Location 2
Dynamic Stiffness	
Average Shear Wave Velocity (m/s)	212.42
Average Elastic Modulus, E (MPa)	180.64
Average Shear Modulus, G (MPa)	75.17
Soil Subgrade Classification	Poorly Graded Clayed Sandy Soil

In general, the dynamic elastic modulus of the subgrade at first location is in good agreement with the result of a loose sandy soil subgrade layer from the study obtained by Nazarian & Stokoe (1986) which is described in Table 2.

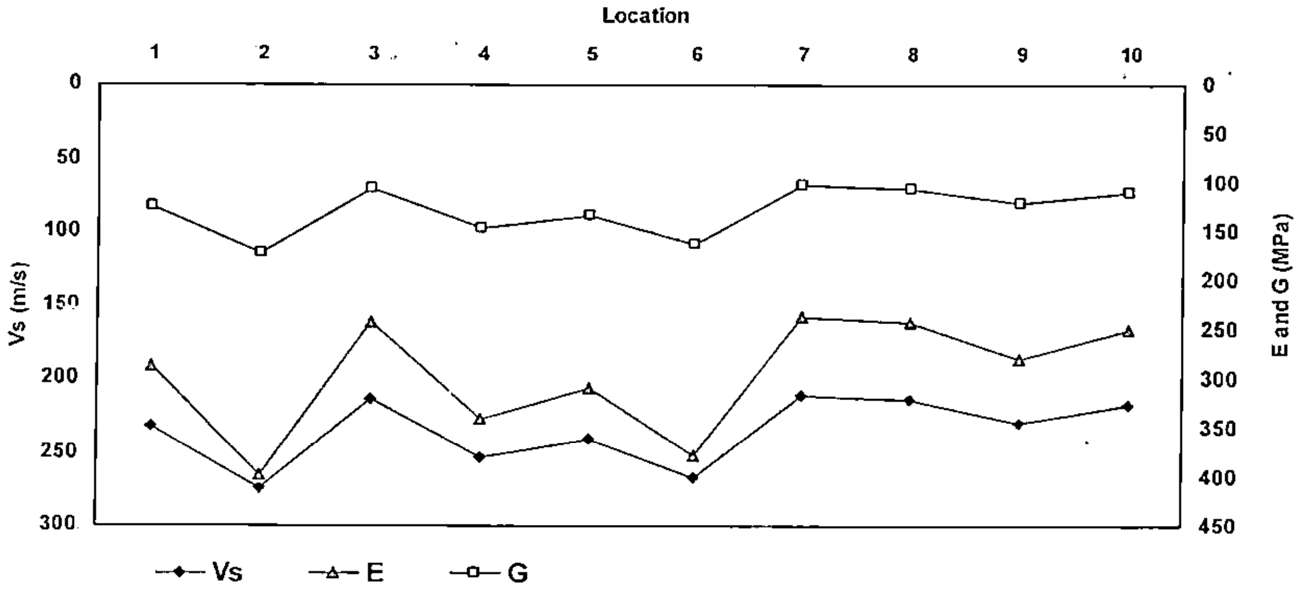

Figure 7. Average dynamic stiffness at second location (State Road, Indonesia) of the tested pavement profile

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). The shear wave velocities from the SASW are then correlated to the DCP 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 that was observed by Rosyidi (2004). The trend of empirical model is shown in Figure 8.

Table 2. Comparison of subgrade shear wave velocity and shear modulus.

Compared parameter	**This study**	**Nazarian & Stokoe (1986)**
Shear wave velocity (m/s)	212.42 m/s	147.5 – 211.9 m/s
Shear Modulus (MPa)	75.17 MPa *Poorly Graded Clayed Sandy Soil*	41.34 – 85.31 MPa *Loose sand*

Figure 8 also shows that the increased in the shear wave velocities correlates well with the DCP values. The coefficients of determination obtained (Figure 8) indicate that the empirical equation derived between the shear wave velocities have significant correlations with the DCP. The determination coefficient R^2 of 0.94 is obtained for the subgrade. The derived equation is where DCP is the penetration per mm of a 8 kg drop weight and V_S is the shear wave velocity in m/s.

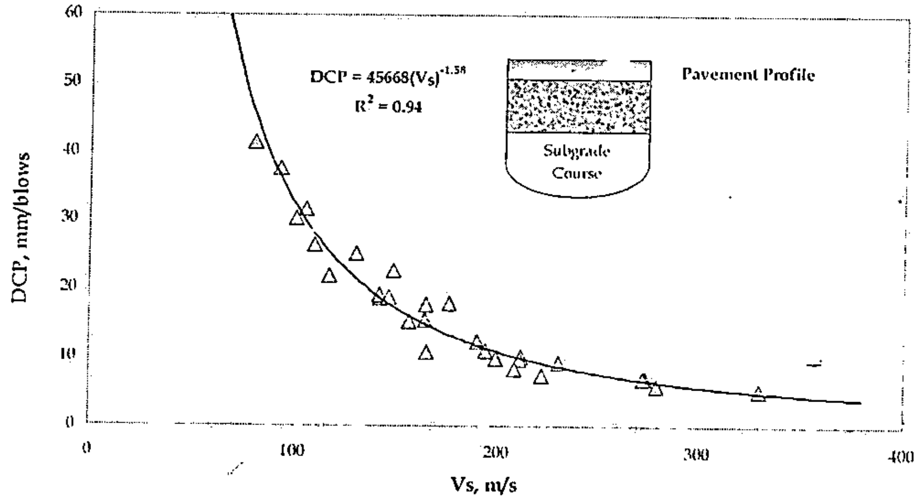

Figure 8. Correlation between the shear wave velocity and DCP for the subgrade layer

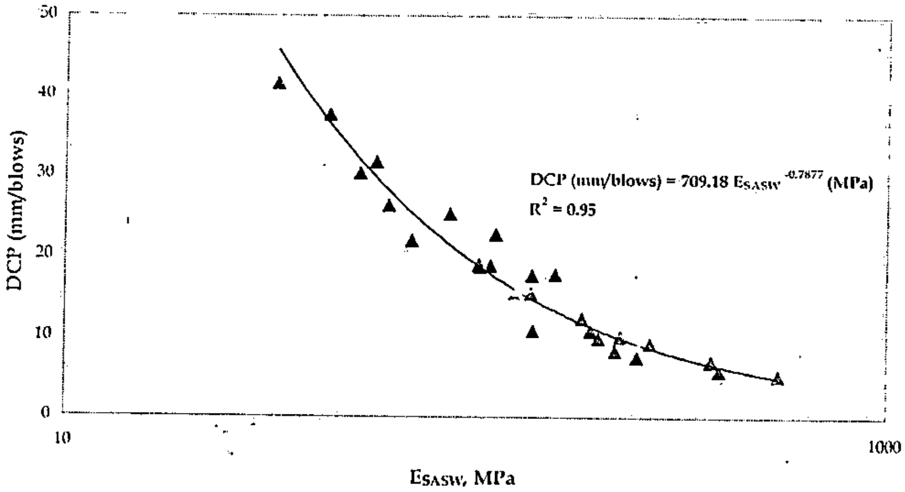

Figure 9. Empirical correlations between the DCP value and the dynamic elastic modulus from SASW for the subgrade layer

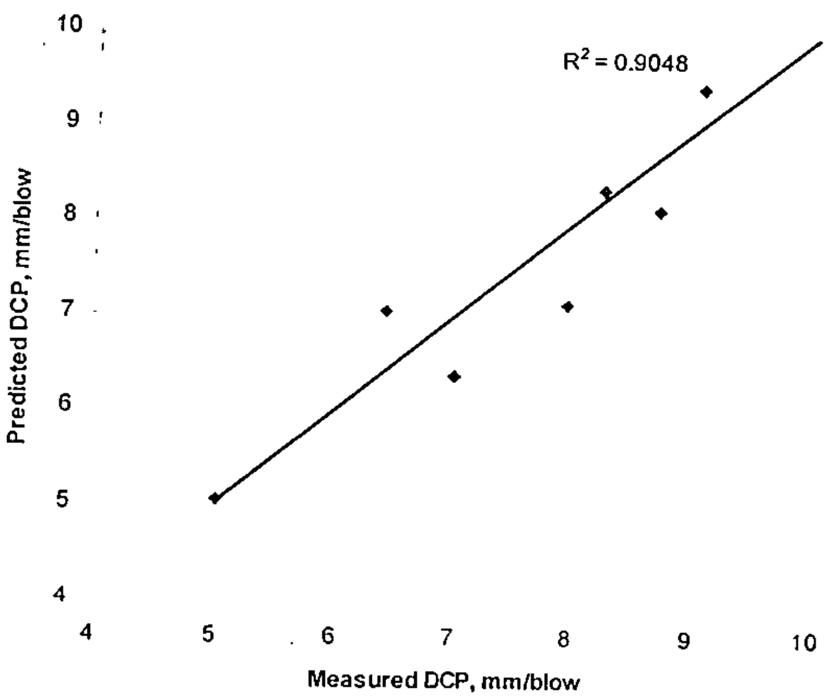

Figure 10. Comparison between DCP values from predicted DCP from equation obtained in this study and field measurement at second location

Figure 9 shows the empirical correlation between the DCP values to the dynamic elastic modulus from SASW for the subgrade layer. The empirical equation obtained was summarized as below :

$$DCP = 709.18\, E_{SASW}^{-0.79} \text{ with } R^2 = 0.95 \qquad (6)$$

where E_{SASW} is the dynamic elastic modulus in MPa. For validate the derived equation in this study, Figure 10 also shows a correlation between the predicted DCP values using Equation 5 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, $R^2 = 0.9048$.

5. CONCLUDING REMARKS

Good agreements were obtained between the measured shear wave velocities and the corresponding dynamic elastic and shear modulus of the soil subgrade from this study as compared to the work of Nazarian & Stokoe (1986). This study has also managed to obtain good empirical correlations between the SASW dynamic parameters with the DCP blow count. The DCP empirical correlation obtained in this study is in good agreement with the DCP values measured for subgrade layers. Thus, 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

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SINOPSIS PENELITIAN LANJUTAN

Penggunaan metode *Spectral Analysis of Surface Wave* (SASW) digunakan untuk mengevaluasi nilai daya dukung tanah lapisan subgrage perkerasan jalan pasca-konstruksi telah terbukti potensinya dalam penelitian Widodo & Rosyidi (2007). Proses data seismik dalam metode SASW ini menggunakan 3 D untuk memperoleh hasil pengujian yang akurat dalam intepretasi mode perambatan gelombang Rayleigh dalam perkerasan jalan Tingkat realibilitas dan signifikasi pengujian SASW dalam pengujian bahan tanah dasar perkerasan jalan diuji melalui berbagai bentuk korelasi eksperimental yang dihasilkan dari pemodelan SASW dan pengujian konvensional di lapangan (DCP). Korelasi eksperimental SASW yang dihasilkan dapat digunakan sebagai referensi mengenai kemampuan metode SASW untuk penilaian perkerasan jalan di Indonesia Namun, penelitian tersebut masih terbatas pada parameter tanah yang tidak terkontrol sehingga aspek dan faktor yang mempengaruhi daya dukung tanah pada lapisan subgrade belum ditinjau. Faktor tersebut diantaranya batas konsistensi tanah yaitu batas cair, plastis dan susut tanah yang akan menghasilkan nilai indeks plastisitas (IP). Nilai IP akan berpengaruh kepada daya dukung tanah. jika IP tinggi maka daya dukung tanah pada kondisi basah akan menjadi turun. Faktor lainnya adalah gradasi tanah dan komposisi fraksi halus. Semakin baik garadasi tanah dengan fraksi tanah halus minimal akan menghasilkan daya dukung tanah yang lebih baik. Potensi pengukuran daya dukung tanah melalui parameter seismik gelombang permukaan menggunakan teknik SASW perlu diinvestigasi ulang terkait dengan faktor di atas