7. Nondestructive measurement techniques and analysis tools
Development of $V_S$-CBR-DCP empirical model for determining dynamic stiffness of pavement base layer using SASW

S.A. Rosyidi
*Muhammadiyah University of Yogyakarta, Indonesia*

M.R. Taha, K.A.M. Nayan, Z. Chik & A. Ismail
*Universiti Kebangsaan Malaysia, Malaysia*

M. Siegfried
*Research and Development Centre for Road and Bridge, Indonesia*

**ABSTRACT:** The stiffness of the base layer is an important parameter for designing the pavement thickness needed to support traffic loadings. It is normally related to the California bearing ratio (CBR). Currently, the CBR could be obtained from laboratory and field testing using Dynamic Cone Penetrometer (DCP). These methods are time consuming, destructive and costly. The spectral analysis of surface waves (SASW) method is hereby introduced as an in situ non-destructive seismic technique to obtain the CBR and DCP values from the measurement and correlation of the dynamic properties of the pavement system. The relationship between the shear wave velocity and dynamic stiffness of the SASW were found to correlate well with DCP and CBR. The empirical correlations of CBR to dynamic stiffness in terms of elastic modulus were found to be similar to the correlation suggested by Shell (1978). Preliminary analysis also indicated that the empirical model was useful for predicting pavement base layer modulus.

1 **INTRODUCTION**

An important feature of a pavement management system is the determination of current and predicts the future condition of the pavement. In order to establish the structural capacity of existing roads, accurate information of the elastic modulus and thickness 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 tire loadings in order to predict the performance, select and design appropriate rehabilitation techniques.

The performance of pavement structures is affected by the stiffness of the base and subgrade layer. In order to effectively measure and evaluate the stiffness of those layers, a non-destructive test (NDT) which is economic and fast is needed. The spectral analysis of surface wave (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. 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. Much of the basis of the theoretical and analytical work of this method for pavement investigation has been developed by Heisey et al. (1982), Nazarian & Stokoe (1984), Røesset et al. (1990, 1991). For practical purposes, an empirical correlation between the seismic parameter (i.e. shear wave velocity) produced by SASW and the conventional pavement assessment (i.e. dynamic cone penetrometer test) is required to enhance assessment of pavement conditions. Experimental investigation of the SASW test on pavement base layer is presented in this paper. An empirical correlation between shear wave velocity obtained
from SASW with the dynamic cone penetrometer (DCP) and the corresponding to the California Bearing Ratio (CBR) will be obtained. The use of DCP test is considered because the method is commonly employed for predicting the bearing capacity of base layer as it is fast and provides the easy understanding of the material parameters.

2 RESEARCH METHODOLOGY

2.1 The Spectral-Analysis-of-Surface-Wave (SASW)

A set of impact sources of various frequencies were used to generate R waves on the pavement surface (Fig. 1a). The propagation of the waves were detected using two receiving accelerometers of piezoelectric DJB A/123/E model (Fig. 1b) and the analog signals were then transmitted to a Harmonie 01 dB (IEC 651–804 Type-I) acquisition box and transferred digitally a notebook computer (Fig. 2). Several configurations of the receiver and the source spacings were required in order to sample different depths. The measurement configuration of the SASW test used in this study is the mid point receiver spacings. In addition, the short receiver spacings of 5 and 10 cm with a high frequency source (steel ball bearings of 10 and 20 g in weight) were used to sample the asphaltic layers.

Figure 1. (a). Various wave sources (b). Accelerometer used in the SASW test.

Figure 2. SASW measurement set up on the pavement surface.
Longer receiver spacings of 20, 40 cm and 80, 160 cm with a set of low frequency sources (a set of hammers of 1, 2 and 5 kg in weight) were employed to sample the deeper base and subgrade layers.

All the signals collected from the recorder were transformed using fast Fourier Transform (FFT) to frequency domain. The $dB/E432$ software was used for the FFT process in the notebook computer. Two functions in the frequency domain are of great importance: (1) the coherence function and (2) the phase information of the transfer function. The coherence function was 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 perfect correlation between the two signals while zero represents no correlation between the two signals. The transfer function spectrum was used to obtain the relative phase shift between the two signals in the range of the frequencies being generated.

A composite experimental dispersion curve from all receiver spacings in one configuration measurement was generated through unwrapping the data of the phase angle from the transfer function and phase velocity calculated using the phase difference method. The time of travel between the receivers for each frequency can be calculated by:

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

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

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

and the corresponding wavelength of the R wave, $L_R$ is written as:

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

By repeating the procedure outlined above and from equation (1) through (3) for each frequency value, the R wave velocity corresponding to each wavelength was evaluated and the experimental dispersion curve from the SASW test was subsequently generated.

The actual shear wave velocity of the pavement profile was then produced from the inversion of the composite experimental dispersion curve. In the inversion process, each layer of pavement profile was assumed as a homogeneous layer extending to infinity in the horizontal direction. The last layer was usually taken as a homogeneous half-space. In this study, a theoretical dispersion curve was then calculated based on the initial profile using an automated forward modeling analysis of the 3-D dynamic stiffness matrix (Kausel & Röesset 1981). The theoretical dispersion curve was ultimately matched to the experimental dispersion curve of the lowest root-mean-square (RMS) error with an optimization technique of the maximum likelihood (Joh 1996). Finally, the profile with the best-fitted (representing the lowest value of RMS) of the theoretical dispersion curve to the experimental dispersion curve was used to represents the most likely pavement profile of the site. The WINSASW version 2.01 software (Joh 1996) was used in this process.

The dynamic elastic modulus of the pavement base material was then easily determined from the following equation:

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

where $E$ = the dynamic elastic modulus, $V_S$ = the shear wave velocity, $g$ = the gravitational acceleration, $\gamma$ = the total unit weight of the material; and $\mu$ = the Poisson’s ratio. Nazarian & Stokoe (1986) explained that the modulus is maximum at a strain below about 0.001%. In this strain range, the modulus of the subgrade materials can be taken as constant.
For this study, the SASW testing was carried out at Universiti Kebangsaan Malaysia (UKM) in Bangi, Selangor, Malaysia. Data were collected from 31 locations with the DCP tests conducted on the same SASW measured centre points.

2.2 **The Dynamic Cone Penetrometer (DCP)**

The 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.

2.3 **The California Bearing Ratio (CBR)**

The relationship between the DCP and the field CBR can be determined using the model derived by Kleyn & van Harden (1983). The result obtained in their study can be written as follows:

\[
\log \text{CBR} = 2.628 - 1.273 \log (\text{DCP})
\]  

where DCP is the penetration mm/blow.

3 **RESULTS AND DISCUSSION**

3.1 **Physical properties of pavement base layer at UKM**

From core samples, the profile of the UKM’s road consists of an asphalt concrete (AC) layer (70 mm thick), and a base of crushed aggregate (400 mm thick) over a subgrade layer.

In Figure 3, the results of the particle size analysis of UKM’s roads show that the material from the base layer can be classified as a well graded class C of the AASHTO classification system.

![Particle size distribution of the base material](image)

Figure 3. Particle size distribution of the base material.
where the course and fine aggregates were gradually distributed. It also shows that particles smaller than 0.075 mm were found to be in the range of 5 to 15%. Therefore, the ratio of the material passing the sieve No.30 over the material passing No. 200 was 0.3 which indicate the absence of gap grading in the base materials.

3.2 Shear wave velocities and elastic modulus

Figure 4 shows an example of the composite experimental dispersion curve of the UKM’s road site obtained from measurements all of the receiver spacings. Subsequently, the SASW inversion process was employed for all of sites to obtain the shear wave velocity and the result is described in Figure 5. From Figure 5, the average inverted shear wave velocity for the base layer from the 31 measured points is 313.1 m/s (with coefficient of variance of 23.43 %) with a range of 162.5 to

![Dispersion Curve](image1)

**Figure 4.** A typical dispersion curve from a complete set of SASW tests on the UKM’s road showing the variation of wavelength with different layers of its profile.

![Shear Wave velocity](image2)

**Figure 5.** Shear wave velocity of base layer from SASW measurement at 31 sites on the UKM’s road.
595.7 m/s and the average dynamic elastic modulus calculated from Equations 4 is 577.8 MPa. In general, the dynamic elastic modulus of the base is reasonable and fall within the range of 100–750 MPa as was obtained by Yoder & Witczak (1975). Similarly, the dynamic elastic modulus of the base layer is also in good agreement with the results of crushed limestone base layer from the study of Nazarian & Stokoe (1986).

### 3.3 Derived empirical correlation

The shear wave velocities from the SASW are then correlated to the DCP and the CBR values for evaluation of the bearing capacities of the base materials. The relationship between the shear wave velocities, CBR and DCP values can also be derived as shown in Figure 6 (for the base layer). Figure 6 also shows that the increase in the shear wave velocities correlates well with the increase in the CBR values, while the shear wave velocities decrease with the DCP values. The CBR values obtained are the field CBR measurements derived from the DCP data using Equation 5.

Figure 6 illustrates that the empirical equation derived between the shear wave velocities have significant correlations with the CBR and DCP value. The correlation coefficient, \( R^2 \) of 0.94 are obtained for the base layer. The derived empirical equations can be written as:

\[
\text{CBR} = 6\left(\frac{V_S}{100}\right)^{1.99} \quad \text{(8)} \\
\text{DCP} = 41861(V_S)^{1.56} \quad \text{(9)}
\]

where CBR = the field California Bearing Ratio in %, DCP = the penetration in mm of a 8 kg drop weight; and \( V_S \) = the shear wave velocity in m/s.

Figure 7 shows the empirical correlation between the CBR and DCP values to the dynamic elastic modulus from SASW for the base layer. The results show a good agreement between the dynamic elastic modulus from the SASW test and the CBR value with a deviation range of \( \pm 20\% \). The empirical equations obtained (\( R^2 = 0.94 \)) can be summarized as follows:

\[
\text{CBR} = 0.097 E_{\text{SASW}} \quad \text{(10)}
\]
where $E_{\text{SASW}}$ = the dynamic elastic modulus obtained from the SASW test in MPa.

The relationship of the CBR value and the dynamic elastic modulus obtained in this study (Equation 10) are almost similar with the empirical equation derived by Shell (1978) which is given by:

$$\text{CBR} = 0.0967 \, E_{\text{dynamic}} \text{ in MPa} \text{ (conversion from }E_{\text{dynamic}} = 1,500 \text{ CBR in Psi)} \quad (12)$$

4 CONCLUSIONS

Good empirical correlations between the shear wave velocity and the dynamic elastic modulus were obtained from SASW dynamic parameters and the DCP blow count (in mm/blow) corresponding to the field CBR (in %) values expressed by Equation 8 to 11. The empirical correlation between the dynamic elastic modulus and the CBR values (Equation 10) was found to be similar to the empirical equation obtained by Shell (1978) for the base layer of the road pavement. An empirical model was developed to obtain equivalent DCP value from the SASW stiffness measurement. The results of this study indicate that there is a potential benefit of SASW method in the assessment of the static stiffness of the base layer for pavement design and evaluation.

ACKNOWLEDGMENT

This study was carried out under IRPA Grant No.09-01-01-0055-EA151 from the Ministry of Science, Technology and Environment, Malaysia and the Kompetisi Penelitian Dosen Grant 2005 from Muhammadiyah University of Yogyakarta, Indonesia. The in situ SASW tests were assisted by Mr. Mecit Kurt, Mr. Wendy Ariyanto and Mr. Eko Rahadi. Their contributions are gratefully acknowledged.
REFERENCES


