Study of the Relationship Between Stiffness Parameters for Base Materials

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Briefing: Study of the relationship between stiffness parameters for base materials

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The stiffness of the base layer is an important parameter for designing the pavement thickness needed to support traffic loads. It is normally related to the California bearing ratio (CBR). The spectral analysis of surface waves (SASW) method is introduced here as an in situ non-destructive seismic technique to obtain the CBR and dynamic cone penetrometer (DCP) values. They are found from measurement of wave velocity and correlation with the dynamic properties of the pavement system. In this study, the relationship between the shear wave velocity and dynamic stiffness of the SASW was found to correlate well with the DCP and CBR values. The empirical correlation of CBR to dynamic stiffness in terms of elastic modulus was found to be similar to a previously suggested correlation. Preliminary analysis also indicates that the empirical model could be used to predict the modulus of pavement base layer.

1. Introduction

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. These parameters are used to calculate the load capacity and to estimate the surface deflection under the centre of wheel loading, in order to predict the performance, and to design the appropriate rehabilitation techniques.

The spectral analysis of surface wave (SASW) is a non-destructive test (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 utilised in different applications over the past decade after advancement and improvement of the well-known steady-state technique (Jones, 1958) and developed by Nazarian and Stokoe (1986). For practical purposes, there is an empirical correlation between the seismic parameter (i.e. shear wave velocity) produced by SASW and the conventional pavement assessment (i.e. the dynamic cone penetrometer (DCP) test), which is required to enhance assessment of the pavement condition.

Empirical correlation is obtained between shear wave velocity, from SASW, and the DCP and with the California bearing ratio (CBR).

2. Research methodology

2.1 The spectral analysis of surface waves

A set of impact sources of various frequencies was used to generate R waves on the pavement surface (Figure 1(a)). The propagation of the waves was detected using two piezoelectric accelerometers, model DJB A/123/E (Figure 1(b)). The analogue signals were then transmitted to a Harmonie 01 dB (IEC 651-804 Type-I) acquisition box and transferred digitally to a notebook computer (Figure 2). The measurement configuration of the SASW test used in this study is the common receiver midpoint (CRM) geometry. The short receiver spacing of 5 and 10 cm with high-frequency sources (steel ball bearings of 10 and 20 g in weight) were used to sample the asphaltic layers. Longer receiver spacings of 20, 40, 80 and 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 sub-grade layers.

All the signals collected from the recorder were transformed using the fast Fourier transform (FFT) to the frequency domain. The dBFA32 software installed in a notebook computer was used for the FFT process and spectrum analysis. Two spectral functions in the frequency domain are of great importance: (*a*) the coherence function and (*b*) the phase information of the transfer function. The coherence function was used to inspect the quality of signals visually that were being recorded in the field. It has a real value

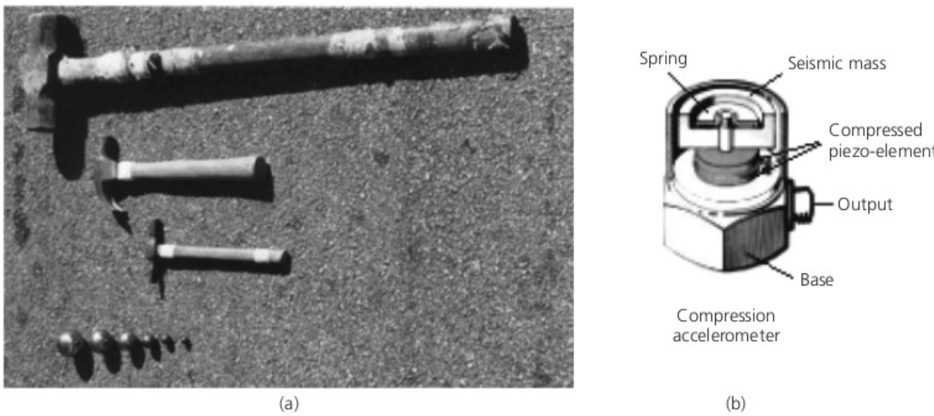

Figure 1. (a) Various wave sources and (b) accelerometer used in the SASW test

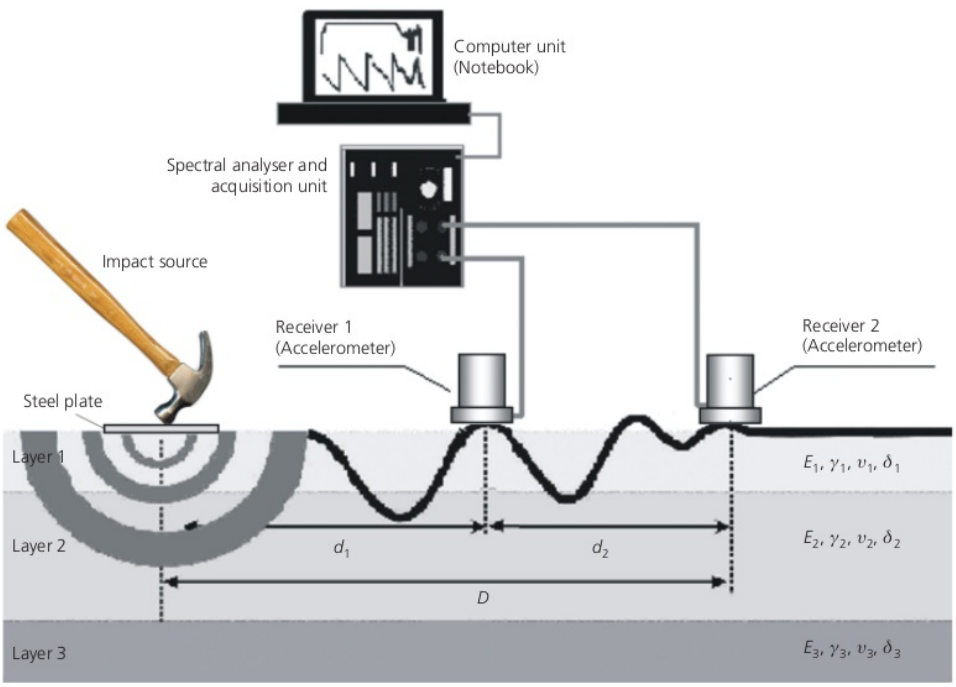

Figure 2. SASW measurement set-up on the pavement surface

between zero and one in the range of frequencies being measured. The value of one indicates a perfect correlation between the two signals received at the accelerometers, whereas 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. The phase velocity was correspondingly calculated using the phase difference method. The time of travel between the receivers for each frequency can be calculated by

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

where f is the frequency, $t(f)$ and $\varphi(f)$ are, respectively, the travel time and the phase difference in degrees at the 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

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

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

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

By repeating the procedure outlined above and from Equations 1 to 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 to be homogeneous and 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 modelling analysis of the three-dimensional dynamic stiffness matrix (Kausel and Röesset, 1981). The theoretical dispersion curve was ultimately matched to the experimental dispersion curve with the lowest root-mean-square (RMS) error with an optimisation technique of the maximum likelihood method (Joh, 1996). Finally, the best fitting dispersion curve with the lowest RMS value was found. The inversion of this curve was used to represent 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

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

where E is the dynamic elastic modulus, V_S is the shear wave velocity, g is the gravitational acceleration, γ is the total unit weight of the material and μ is the Poisson's ratio. At a strain below about 0·001% the modulus of the sub-grade materials can be taken as constant.

In 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

The DCP uses an 8 kg steel mass falling from a height of 50·8 cm (20 inches) striking an anvil a number of times, causing a penetration of 3·8 cm (1·5 inches). The anvil is attached to a cone with a 60° vertex angle seated in the bottom of a hand-augered hole. The number of blows required to drive the embedded cone to a depth of 4·4 cms (1·75 inches) have been correlated to N values of the standard penetration test (SPT). The penetration per hammer-drop interval is reported in terms of DCP index (mm/blow).

2.3 The California bearing ratio

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

$$\log(\mathrm{CBR}) = 2{\cdot}628 - 1{\cdot}273\log(\mathrm{DCP}) \quad (5)$$

where DCP is the penetration in mm/blow.

3. Results and discussion

3.1 Physical properties of the pavement base layer at UKM

From core samples, the profile of the road at UKM where the tests were conducted, was shown to consist of an asphalt concrete (AC) layer (70 mm thick), on a base of crushed aggregate (400 mm thick), overlying a sub-grade 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 American Association of State Highway and Transportation Officials (AASHTO) classification system (AASHTO, 2008) where the coarse and fine aggregates

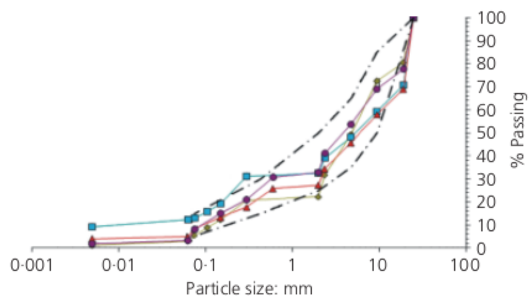

Figure 3. Particle size distribution of the base material

are gradually distributed. It also shows that particles smaller than 0·075 mm were found to be in the range 5 to 15%.

3.2 Shear wave velocities and elastic modulus

Figure 4 shows an example from the result of the composite experimental dispersion curve obtained from measurements from all the receiver spacings. Subsequently, the SASW inversion process was employed for all sites to obtain the shear wave velocity, and the result is as shown in Figure 5. From Figure 5, the average inverted shear wave velocity for the base layer from the 31 measured points is 313 m/s with a range of 162 to 595 m/s and a coefficient of variance of 23%. The calculated average dynamic elastic modulus of the base layer of 577 MPa is then obtained from Equation 4. In general, the dynamic elastic modulus of the base layer is reasonable, and falls within the range of 100 to 750 MPa as reported by Yoder and Witczak (1975).

3.3 Derived empirical correlation

The shear wave velocities from the SASW are then correlated with the DCP and the CBR values for the evaluation of the bearing capacity of the base material. The relationship between

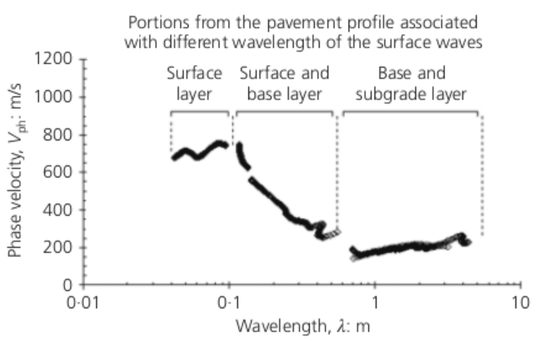

Figure 4. A typical dispersion curve from a complete set of SASW tests at UKM showing the variation of wavelength with different layers of the road profile

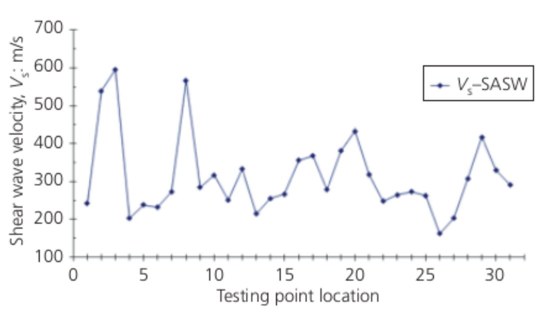

Figure 5. Shear wave velocity of the base layer from SASW measurement at UKM

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 velocity correlates well with the increase in the CBR values, whereas the shear wave velocities increase with decreasing DCP index according to a power (see Equation 9). The CBR values obtained are derived from the DCP data using Equation 5.

Figure 6 illustrates that the empirical equation derived between the shear wave velocities shows significant correlation ($R^2 = 0{\cdot}94$) with the CBR and DCP value from the base layer. The derived empirical equations can be written as

$$\text{6.} \quad \text{CBR} = 6\left(\frac{V_S}{100}\right)^2$$

$$\text{7.} \quad \text{DCP} = 41861(V_S)^{-1{\cdot}56}$$

where CBR is the field California bearing ratio in %, DCP is the penetration in millimetres of a 8 kg drop weight and V_S is 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 ±20%. The empirical equations obtained with $R^2 = 0{\cdot}94$ can be summarised as follows

$$\text{8.} \quad \text{CBR} = 0{\cdot}097\ E_{\text{SASW}}$$

$$\text{9.} \quad \text{DCP} = 698{\cdot}21\ E_{\text{SASW}}^{-0{\cdot}78}$$

where E_{SASW} is 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) is similar to the empirical equation derived by Shell (1978) with conversion of $E_{\text{dynamic}} = 1500$ CBR in psi and is given by

$$\text{10.} \quad \text{CBR} = 0{\cdot}0967\ E_{\text{dynamic}}(\text{in MPa})$$

3.4 Validation of empirical correlation

An experimental study was carried out in order to validate the empirical equation derived from Equation 6. The SASW and DCP tests were conducted in the same location on the physical

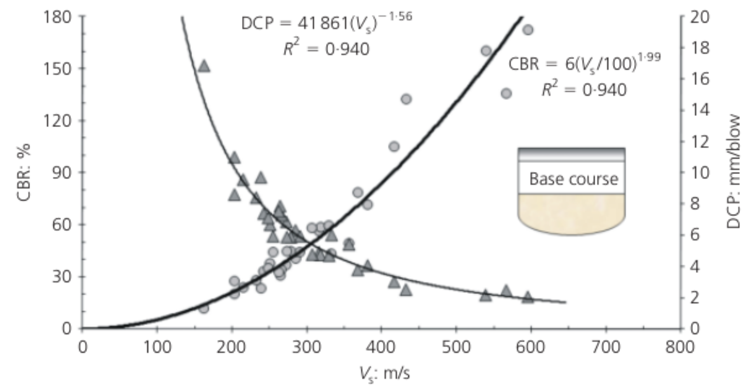

Figure 6. Correlation between the shear wave velocity, DCP and CBR for the base layer

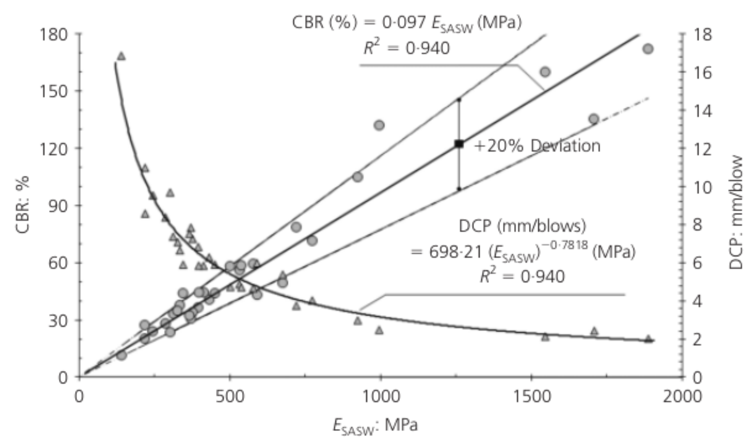

Figure 7. Empirical correlation between the CBR, DCP value and the dynamic elastic modulus from SASW for the base layer

pavement model. The pavement model consisted of 5 cm of asphalt concrete (AC) layer as a surface layer, 15 cm of AC base layer as a structural layer, 20 cm of unbound aggregate materials of base layer over a compacted sub-grade layer. The properties of the base layers are shown in Table 1.

Unbound aggregate materials of crushed gravel were used in this study which typically contains 87% of the coarse aggregate particles (maximum aggregate size of 7·6 cm). Cubic particles of unbound aggregate materials were chosen with a small amount of flat and elongated particles (i.e. less than 7%). In order to produce the high stiffness of the base layer, well-graded materials were used. The amount of fines was limited to around 0·1% to maintain the material stiffness and to promote drainage. At MDD (maximum dry density), the bearing capacity of unbound aggregate materials was measured using the CBR test and was found to be 76%.

An example of the CBR profile from the field–DCP test is shown in Figure 8. The trend line of V_S obtained from the SASW test to the CBR profile is shown to be similar where low values of CBR are in correspondence with low shear wave velocity. Equation 6 has a similar trend to the best fit curve of the measured data (Figure 9). However, the deviation of the empirical equation can be clearly observed when the shear wave velocities are greater than about 280 m/s.

Properties	Standard	Value
Flat and elongated particles	ASTM D4791 (ASTM, 2010)	7%
Material passing sieving no. 200 (0·075 min)	ASTM C136 (ASTM, 2006b)	0·1%
Specific gravity	–	2·758
Maximum dry density (γ_{max})	ASTM D 1157 (ASTM, 2009)	2·25 g/cm^3
Optimum moisture content W_{opt})		6·3%
CBR value at MDD (2·25 g/cm^3)	ASTM D1883 (ASTM, 2007)	76%
Abrasion value from Los Angeles test	ASTM C131 (ASTM, 2006a)	27·9%

Table 1. Physical properties of coarse aggregate in base layer materials

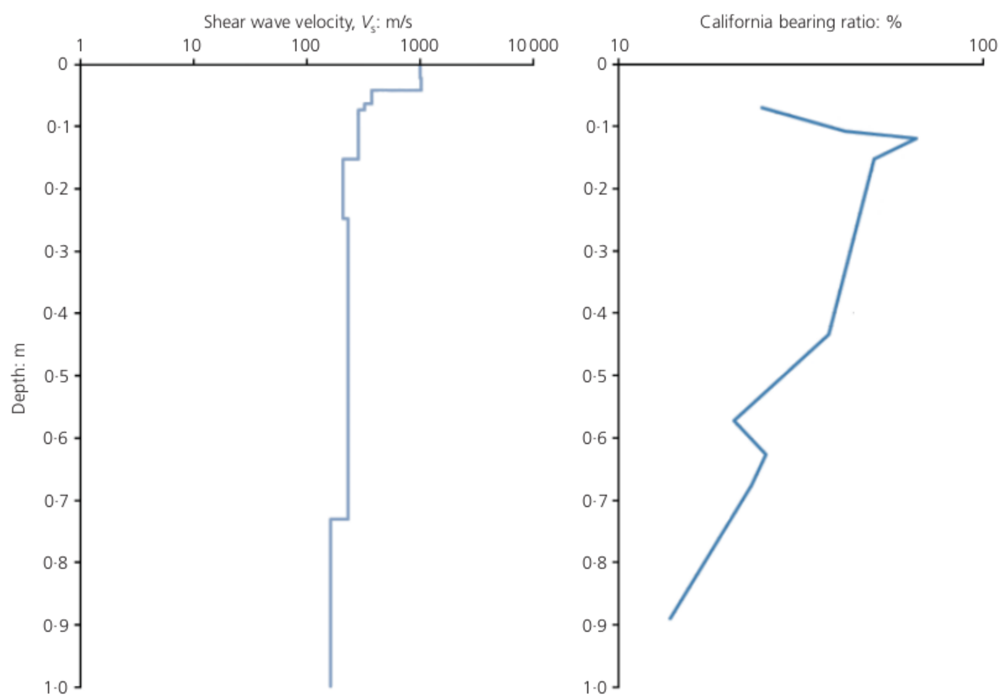

Figure 8. Comparison of the shear wave velocity profile obtained from SASW tests and the field CBR profile from DCP tests for the pavement model

4. Conclusions

Good empirical correlations of shear wave velocity and dynamic elastic modulus were obtained with respect to the DCP blow count (mm/blow) and derived CBR (%) values. The empirical correlation between the dynamic elastic modulus and the CBR values 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 the equivalent DCP values from SASW stiffness measurement. The results of this study indicate that there is a good potential for the application of the SASW method in the assessment of the base layer for the design and evaluation of the pavement.

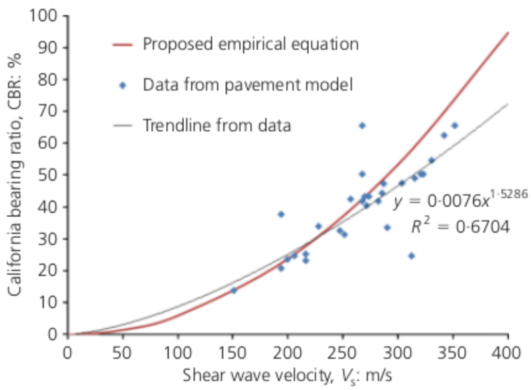

Figure 9. Comparison between empirical equation and measured data from the pavement model

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