

MEASUREMENT OF SUBGRADE STIFFNESS USING THE SASW METHOD

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ABSTRACT

The knowledge of the in-situ strength and stiffness of the ground is normally required for the design monitoring and evaluation of highway pavement so as to ensure an adequate margin of safety. In order to estimate the stiffness of the pavement foundation a method called the spectral analysis of surface wave (SASW) has been developed. Stiffness parameters from the shear and Young's modulus derived from the SASW measurements are obtained at a small strain level of <0.001%. At this strain level the soil is linearly elastic and the use of elastic theories is thus justified. The method consists of generation, measurement and processing of the dispersive Rayleigh waves recorded from two vertical transducers. Subsequently, the dispersive data are inverted and the shear wave velocity versus depth of the site is obtained. The results presented in this paper showed that the SASW method is able to determine reliable stiffness parameters of the subgrade layer of the pavement profile. In situ subgrade bearing capacity test using the 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. An empirical relationship between the DCP value and the soil stiffness from SASW measurements was also established for practical applications.

Keywords: SASW, shear modulus, shear wave velocity, pavement subgrade layer

1. INTRODUCTION

An important feature of a pavement management system is its ability to determine the current and to 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 to design appropriate rehabilitation techniques.

The performance of pavement structure is most affected by the stiffness of the subgrade layer. In order to effectively measure and evaluate the stiffness of the subgrade layer, 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 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 1962) 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

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evaluation of railway ballast. The purpose of this paper is to describe the theory, role and method of the SASW in the evaluation of the subgrade layer. Typical results from a case study are presented herein for the structural assessment of an existing asphaltic pavement.

2. THEORY

2.1 The spectral analysis of surface wave

The SASW method is based on the particles motion of Rayleigh wave in heterogeneous media. The energy of Rayleigh waves from the source propagate mechanically along the surface of media and their amplitude decrease rapidly with depth. Particle motions associated with Rayleigh 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, Rayleigh wave velocity does not vary with frequency. However, Rayleigh 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 Rayleigh 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:

$$\lambda = \frac{V_s}{f} \quad (1)$$

where f is the frequency and V_s is shear wave velocity. The higher and low frequency waves groups needed can be generated by various transient sources of different weights and shapes. Waves of low frequency for the subgrade layer could be generated from hammer weights of 3 to 5 kg (Rosyidi et al. 2001).

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 $\frac{1}{2}$ and less than 3 receiver spacings. The time of travel between the receivers for each frequency can be calculated by:

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

where f is the frequency, $t(f)$ and $\phi(f)$ is 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, Rayleigh wave velocity, V_R or the phase velocity at a given frequency is simply obtained by:

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

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

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

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 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 dynamic stiffness matrix method (Kausel & Roesset 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).

The shear moduli of the subgrade materials can then be determined from the following equation (Yoder & Witzcak 1975):

$$G = \frac{\gamma \cdot V_s^2}{g} \quad (5)$$

where G is the dynamic shear modulus, V_s the shear wave velocity, g the gravitational acceleration and γ the total unit weight of the material. Nazarian & Stokoe (1986) explained that the modulus parameter of material is constant and is maximum at a strain below about 0.001 %. In this strain range, modulus of the subgrade materials is also taken as constant.

2.2 The dynamic cone penetrometer

The dynamic cone penetrometer (DCP) is used as a rapid means of assessing the sequence, thickness and in-situ bearing capacity of the unbound layers and underlying subgrade that comprise the pavement structure. The original DCP was developed in 1959 by the late Professor George F. Sowers. The DCP uses a 8 kg steel mass falling 20 in (50.8 cm) that strikes the anvil to cause penetration of a 1.5 in (3.8 cm) diameter cone (60° vertex angle) that has been seated in the bottom of a hand augered hole. The blows required to drive the embedded cone a depth of 1-3/4 in have been correlated by others to N values derived from 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. METHODOLOGY

3.1 Experimental Set Up

An impact source on a pavement surface is used to generate Rayleigh waves. These waves are detected using two acceleration receiver where the signals are recorded using a spectrum analyzer for post processing (Figure 1). Several configurations of the receiver and the source spacings are required in order to sample different depths. The best configuration in the SASW is the mid point receiver spacings (Heisey et al.1982).

Short receiver spacing of high frequency (short wavelength) is used to sample shallow layers while long receiver spacing of low frequency (long wavelengths) is used to sample deeper layers. For detecting the subgrade of deeper layers of the pavement profile, the low frequency (long wavelength) with receiver spacings of 80 and 160 cm were implemented. The SASW testing was carried out on a road inside the campus at Universiti Kebangsaan Malaysia (UKM) in Bangi. Data were collected from 10 sites together with the DCP tests conducted on the same SASW measured centre points.

3.2 Data Analysis

All the data collected are transformed using the Fast *Fourier* Transform (FFT) to frequency domain by a spectrum analyzer. 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 2 shows a typical set of the coherence and the spectrum of 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 for all the receiver spacings are generated.

By repeating the procedure outlined and using equation (2) through (4) for each frequency value, the Rayleigh wave velocity corresponding to each wavelength is evaluated and the experimental dispersion curve is generated.

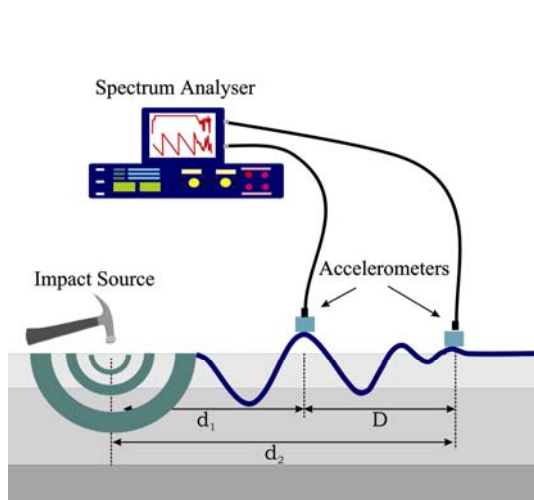


Figure 1: Field measurement configuration.

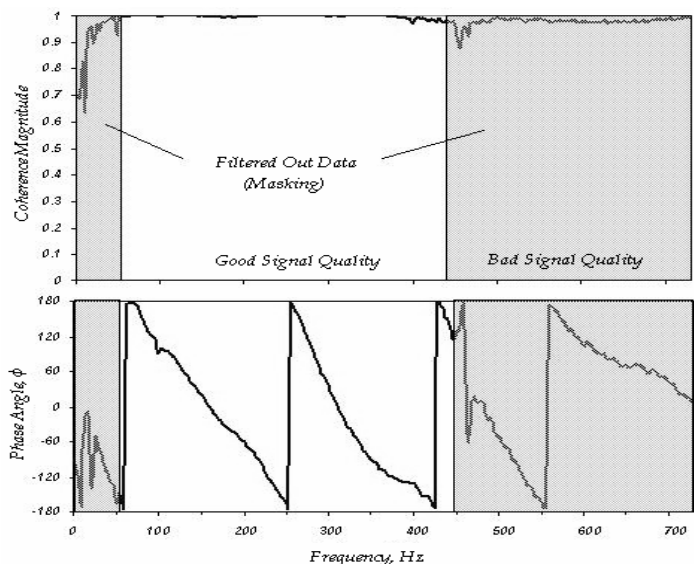


Figure 2: The coherence and the transfer function spectrum for an 80 cm receiver spacing.

4. RESULT AND DISCUSSION

The road profile consists of an asphalt layer (70 mm thick), a base of crushed aggregate (400 mm thick) over a subgrade. Material properties and thicknesses of the pavement layers are shown in Figure 4. The composite dispersion curve for site 1 and 2 obtained are as shown in Figure 3 where the two dispersion curves for wavelengths ranging from 0.7 m downwards representing the subgrade layer with the minimum phase velocity of 110 m/s and the maximum phase velocity of 245 m/s are shown.

From the 3 D forward modeling of the stiffness matrix method (Kausel & Roesset 1981), the average inverted shear wave velocity for the 10 measuring points is 178.42 m/s with a range of 116 to 263 m/s. Figure 4 shows the shear wave velocity and shear modulus profile for site 1 from the inversion of the composite experimental dispersion curve.

The average shear modulus of the subgrade material from the analysis is found to be 69.78 MPa. From on the average shear modulus, the subgrade material may be classified as a sandy soil material based on the result of Puri (1969) and Nazarian & Stokoe (1986). The dynamic shear modulus, G from the SASW

were then correlated to the DCP value in order to evaluate the soil bearing capacity with the coefficient of R^2 of 0.9465. The following equation is then obtained:

$$DCP = 328.16 (G)^{-0.7877} \quad (6)$$

The shear wave velocities and their corresponding shear modulus from this study were compared in Table 1 with the results of SASW testing that have been carried out by other workers, such as Puri (1969), Nazarian & Stokoe (1986) and Al Hunaidi (1998).

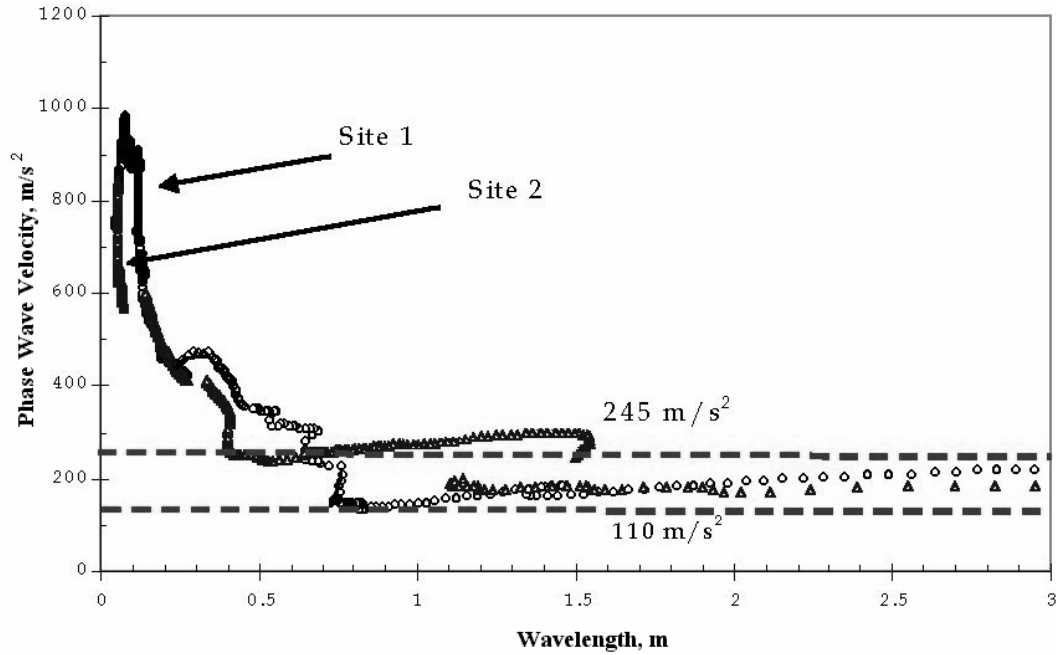


Figure 3: Composite experimental dispersion curves from site 1 and 2.

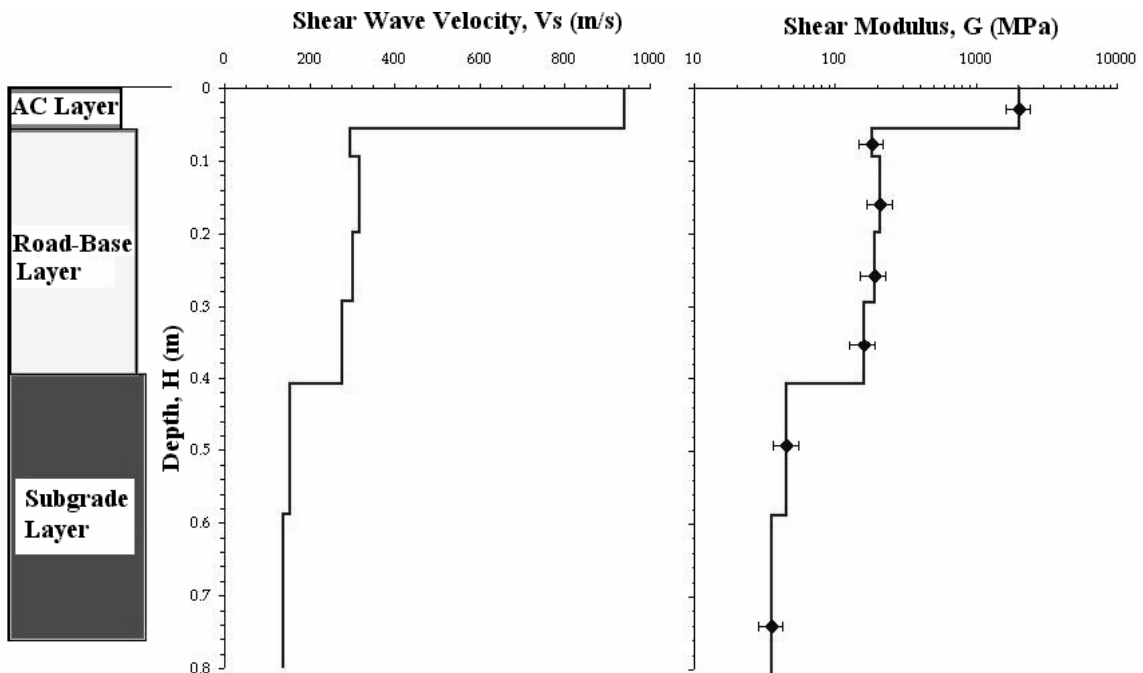


Figure 4: Shear wave velocity and shear modulus profile from inversion analysis compared to the actual road profile.

In general, the results were shown to be in good agreement. Nazarian & Stokoe (1986) conducted the SASW method to characterize the subgrade where the shear wave velocity obtained was between 147.5 – 211.9 m/s (compared to 178.419 m/s obtained in this study). Al Hunaidi (1998) on the other hand obtained values ranging between 80 – 300 m/s. Puri (1969) obtained the dynamic properties of silty sand using free vertical vibration stress waves measured at 1.0×10^{-4} % strain level. The shear modulus obtained in this study is 69.779 MPa compared to 64.75 MPa by Puri (1969) and 41.34 – 85.31 MPa by Nazarian & Stokoe (1986).

Table 1: Comparison of subgrade shear wave velocity and shear modulus.

Compared parameter	This study	Puri (1969)	Nazarian & Stokoe (1986)	Al Hunaidi (1998)
Shear wave velocity (m/s)	178.42 m/s	---	147.5 – 211.9 m/s	80 – 300 /ms
Shear Modulus (MPa)	69.78 MPa Sandy soil	64.75 MPa Poorly graded fine silty sand	41.34 – 85.31 MPa Loose sand	---

5. CONCLUSIONS

Good agreement was obtained between the measured shear wave velocity and its corresponding shear modulus from this study as compared to Puri (1969), Nazarian & Stokoe (1986) and Al-Hunaidi (1998). This study has also managed to obtain a good empirical correlation between the DCP blow count and the dynamic shear modulus (G). Thus, the SASW method is able to characterize the stiffness of the pavement subgrade layer in terms of shear wave velocity and its corresponding dynamic shear modulus satisfactorily for pavement design and evaluation.

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