A HIGH-ACCURACY CALIBRATION METHOD FOR THICKNESS MEASUREMENTS OF ASPHALT PAVEMENT USING GROUND-PENETRATING RADAR

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ABSTRACT

To improve the measurement accuracy of the thickness of asphalt concrete layer, an optimal calibration method for ground-penetrating radar (GPR) measurements is presented by comparing twelve kinds of algorithms. Based on the layer-stripping inversion, one through four calibrating coefficients are introduced into the calculation equations of thickness. Specifically, the reflected signals are reconstructed by fitting smoothing spline in three calibration procedures. With the optimal calibration procedure, the thickness measurement errors can be effectively decreased. This is a critical study of the quality assessment of hot-mix asphalt (HMA) paving using GPR.

1. INTRODUCTION

Providing a safe and non-destructive method of subsurface investigations, ground-penetrating radar (GPR) has been used since the 1980s to measure the thickness of pavement layers (Loulizi et al., 2003). The past two decades have witnessed a tremendous increase in the use of GPR technology that has several major advantages, such as high-rate data acquisition, quasi-continuous measurements and mapping of the individual layers.

The precision of GPR data is of increasing interest. Unfortunately, most existing commercial GPRs are based on the pulse technique and employ wide-duration pulses, which result in low resolution and limit the systems' abilities to accurately determine subsurface layer thickness (Jeong Soo et al., 2004). The GPR systems designed for a specific purpose can surely improve the quantitative measurements, but it is unrealistic to expect owners to scrap their current instrumentation right now.

It has been determined that the deviation of GPR measurement results from (a) heterogeneous ground properties, e.g. variable density, water content and air void content; (b) medium attenuation (Huang and Su, 2005); (c) the height of the antenna above the road, which is difficult to keep constant at high speed (Gordon *et al.*, 1998); (d) a rough surface, which scatters the incident pulse rather than reflects it neatly; (e) radio noise (Olhoeft, 2002); and (f) the variation in the time base of the instrumentation used (Jacob and Hermance, 2005), etc. The difference between the ideal layer-stripping model and the actual condition results in non-linear deviation of measurement. Based on layer-stripping inversion, one through four calibrating coefficients is introduced into the calculation equations of thickness in this study. The optimal calibration method can be found finally by comparing the calibration effects.

2. BACKGROUND

GPR pavement thickness data were collected for: (a) structural characterisation of existing pavements to estimate their remaining service life; (b) network level surveys; (c) supplementing FWD data in the calculation of layer moduli; (d) pavement design purposes, e.g. to check if the pavement is thick enough for recycling milling; and (e) quality control (Saarenketo and Scullion, 2000). Pavement layer thickness is an important factor that determines the quality of newly constructed pavements and overlays. For asphalt pavement, GPR is by far the most established technology (other than coring) for measuring pavement thickness. Evaluation studies have been carried out by SHRP, Mn/ROAD, Kentucky Transportation Center and the FHWA, all of which have documented the accuracy of GPR asphalt thickness vs. core samples (Wenzlick et al., 1999; Al-Qadi et al., 2005; Willett et al., 2006; Maser et al., 2006). These studies have shown that for newly constructed pavements, the deviation between GPR and core results range from 2 to 5% of the total thickness. This paper suggests that higher accuracy could be realised by an appropriate calibration procedure.

3. LAYER THICKNESS ESTIMATION FROM GPR DATA

GPR has been tentatively applied in HMA quality assessment for the pavement of the Yangjiang-Maoming expressway, Guangdong Province, China. The pavement is a typical structure, which mainly includes a three-layered asphalt surface layer, cement-bound granular base layers and subgrade. The monostatic GPR system used in this case is an impulse radar with an air-coupled horn antenna deployed at about 500 mm above the pavement surface. The transmitted pulse width is 1.0 ns. To assess the uniformity of the thickness and degree of compaction of newly paved asphalt concrete, the thickness and relative permittivity of the surface layer need to be precisely estimated based on GPR data. Although the exact value of the permittivity of HMA mixtures may not be measured conveniently, the accuracy of estimated permittivity can be inferred through thickness. Therefore this study places emphasis on thickness estimation.

Electromagnetic inversion is a useful tool for quantitative analysis in short-range applications of impulse radars (Spagnolini, 1997). To estimate multi-layered media properties using monostatic radar, a layer-stripping algorithm is widely used. As an ideal layer-stripping model, each pavement layer is a mixture of particles embedded in a homogeneous matrix. Since particle size is considered to be small compared to the pulse resolution, the pavement is assumed to be horizontally layered and homogeneous within each layer. Moreover, plane wave approximation is usually understood in the layer-stripping approach. Currently, the permittivity and thickness of the surface layer can be estimated from GPR data as follows (Attoh-Okine, 1996):

$$\sqrt{\varepsilon_{r1}} = \frac{A_m + A_0}{A_m - A_0} \quad (1)$$

$$h_1 = \frac{ct_1}{2\sqrt{\varepsilon_{r1}}} \quad (2)$$

Assuming $\lambda = A_0 / A_m$, then

$$h_1 = 0.5ct_1 \Big/ \left(\frac{1+\lambda}{1-\lambda}\right) \quad (3)$$

where:

ε_{r1} is the relative permittivity of the surface layer.

A_0 is the amplitude of the surface reflection.

A_m is the amplitude of the reflected signal collected over a flat metal plate placed on the pavement surface.

h_1 is the thickness of the surface layer.

c is the speed of light in free space, $c \approx 3 \times 10^8 m/s$.

t_1 is the time delay between the received pulses reflected from the top and bottom of the surface layer.

The accuracy of equation (3) can easily be checked by laboratory or field tests. Our field tests at a paving spot have shown that the relative errors range from 0.1% to 7.57%, the mean relative error is 3.98%, and the mean absolute error is 7.26 mm (see Table 1 for details). Although they may be accurate enough for some general purposes, the corresponding thickness data could not be considered as plausible evidence in the project of quality assessment of HMA paving.

Table 1. Estimated surface layer thicknesses without calibration.

Sample No.	Core thickness (mm)	h_1 estimated by "Method 1" (no calibration) (mm)	Relative error	Absolute error
1	190	192.33	0.0122	2.33
2	179	171.68	0.0409	7.32
3	190	180.75	0.0487	9.25
4	183	173.77	0.0504	9.23
5	170	162.61	0.0435	7.39
6	182	168.22	0.0757	13.78
7	196	192.62	0.0173	3.38
8	200	199.81	0.0010	0.19
9	193	185.00	0.0415	8.00
10	174	169.96	0.0232	4.04
11	180	168.71	0.0627	11.29
12	179	168.08	0.0610	10.92
Mean value			**0.0398**	**7.26**

4. CALIBRATION METHODS

Based on the ideal layer-stripping model, equation (3) inevitably results in a deviation of measurement. According to equations (1) and (2), the evaluation value of thickness depends on the corresponding time delay and the relative permittivity. The amplitude error directly determines the accuracy of relative permittivity, and the accuracy of the time delay and the relative permittivity affect the thickness measurement. Thus $\sqrt{\varepsilon_{r1}}$, λ and t_1 should be calibrated and the thickness of the surface layer can be determined from:

$$\tilde{h}_1 = 0.5c\left(k_5 t_1 + k_6\right) \Big/ \left(k_1 \frac{1+\left(k_3\lambda + k_4\right)}{1-\left(k_3\lambda + k_4\right)} + k_2 \right) . \quad (4)$$

In view of the complexity of the wave propagation in pavement materials, which is not exactly homogeneous within each layer, the other uncertain factors could not be entirely disregarded, e.g., the wave speed in air would drift with the variation of the air moisture or density. Furthermore, the ideal model itself should be rectified. Therefore, another calibration equation is simply given as:

$$\tilde{h}_1 = 0.5ck_7t_1 \Big/ \left(\frac{1+\lambda}{1-\lambda} \right) + k_8 \quad (5)$$

where k_i (i = 1 to 8) is the calibrating coefficient and $\tilde{h}_1$ is the calibrated thickness of the surface layer.

To decide t_1 and λ, the wave crest and trough of every received pulse must be well located. When the thickness is calculated by equations (4) and (5), the wave crest and trough are searched among the sampled points. Actually, the sampling interval is a constant unless the GPR is adjusted intentionally, which means the wave crests or troughs are probably located between two neighboring sampled points (see Figure 1). Considering that the bias of the location can directly affect t_1, A_0 and A_m, the spline smoothing approach is introduced into calibration methods, equation of which is expressed as:

$$\tilde{h}_1 = 0.5c\left(k_5t_1^* + k_6\right) \Bigg/ \left(k_1 \frac{1+\left(k_3\lambda^* + k_4\right)}{1-\left(k_3\lambda^* + k_4\right)} + k_2 \right) \quad (6)$$

$$\tilde{h}_1 = 0.5ck_7t_1^* \Big/ \left(\frac{1+\lambda^*}{1-\lambda^*} \right) + k_8 \quad (7)$$

where t_1^* and λ^* are calculated using the fitted curve of the received pulses.

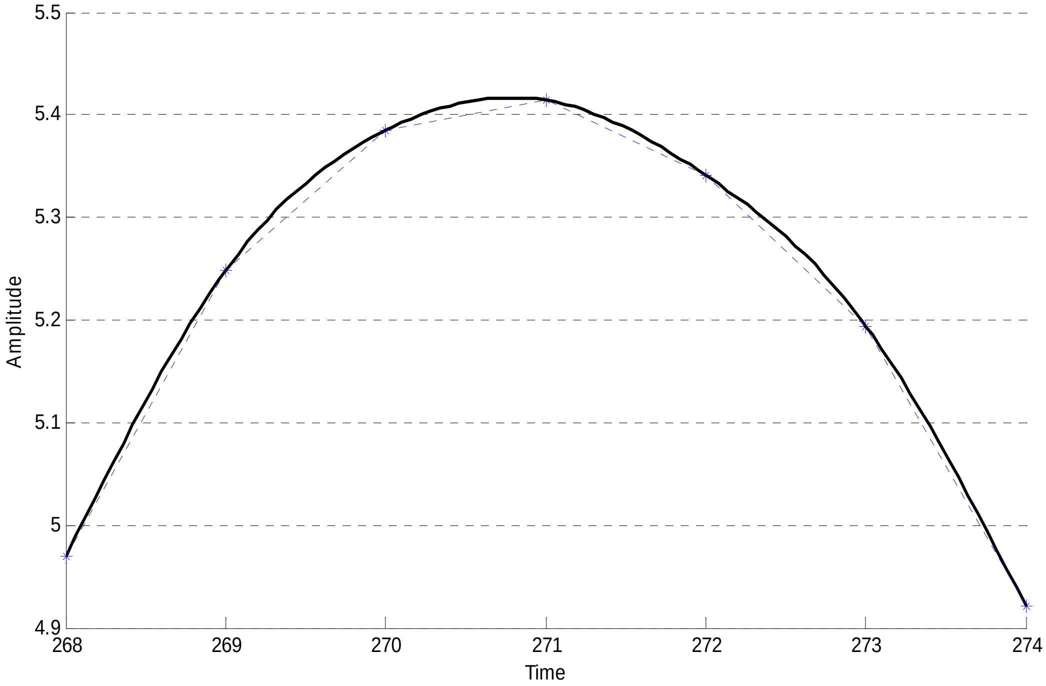

Figure 1. A local sketch map of a reflected signal reconstructed by fitting smoothing spline.

5. SELECTION AND DETERMINATION OF CALIBRATION FACTORS

To determine the calibration factors, it is necessary to obtain enough data including received pulses and the precise layer thickness. The general method of obtaining data is to drill a core after the GPR test. Subsequently, the calibrating coefficients can be determined through non-linear regression analysis based on the least squares method.

Since GPR is commonly regarded as a non-destructive approach, the pavement should not be drilled too much. Moreover, the more factors selected, the more data will be required. Therefore in this study, 12 kinds of calibration methods (not including the two items without calibrating factors) based on equations (4) to (7), are selected respectively with no more than four calibrating factors (see Table 2).

Table 2. Selected calibrating factors in calibration methods.

Method	Selected calibrating coefficients	Corresponding equation
1	none	(5)
2	k_1	(4)
3	k_3	(4)
4	k_1,k_2	(4)
5	k_3,k_4	(4)
6	k_1,k_2,k_3	(4)
7	k_1,k_2,k_3,k_4	(4)
8	k_3,k_5,k_6	(4)
9	k_3,k_4,k_5,k_6	(4)
10	k_7,k_8	(5)
11	none	(7)
12	k_1,k_2	(6)
13	k_3,k_4,k_5,k_6	(6)
14	k_7,k_8	(7)

Remark: The non-selected coefficients are equal to 1 or 0 when the subscripts are odd or even numbers respectively.

6. EXPERIMENTAL RESULTS

When a section of the surface layer mentioned above was finished, 22 spots at random locations with about 200 m proportional spacing were marked. After a GPR static check was performed in sequence, we carefully sampled drill cores which were subsequently sent to the laboratory to test quality performance, including the precise thickness of the asphalt concrete layer. Ten of the 22 cores were selected at random and used to compute the calibration factors, while the others were used to evaluate the effect of the calibration methods.

The relative errors of the thickness of the 12 samples calibrated by different methods are shown in Figure 2. The mean relative error and summed square of residuals (see Table 3) provide a quantitative evaluation of the effects of different methods. Unexpectedly, the methods with curve fitting, which entails a higher computational cost, are not so ideal. It is clear that Method 9 is the optimal one. Table 4 presents the calibration results of Method 9 in detail, which reveals that the relative error ranges from 0.03% to 3.94%, the mean relative error has decreased from 3.98% to 1.35%, and the mean absolute error has dramatically decreased from 7.26 mm to 2.48 mm compared to Table 1. Such considerable accuracy can meet our purposes of quality assessment very well.

Table 3. Comparison of the effect of all calibration methods.

Method	Mean relative error (%)	Summed square of residuals (mm^2)
1	3.98	812.60
2	2.21	386.41
3	2.17	379.42
4	2.02	355.00
5	2.00	346.75
6	2.01	348.13
7	1.90	299.53
8	1.40	126.95
9	1.35	121.09
10	1.45	136.76
11	4.91	1139.44
12	2.03	312.96
13	1.71	185.99
14	1.64	186.54

Table 4. Calibration results of Method 9.

Sample No.	Core thickness (mm)	h1 estimated by Method 9 (mm)	Relative error	Absolute error
1	190	197.48	0.0394	7.48
2	179	181.00	0.0112	2.00
3	190	186.84	0.0166	3.16
4	183	184.00	0.0055	1.00
5	170	172.54	0.0149	2.54
6	182	177.47	0.0249	4.53
7	196	195.94	0.0003	0.06
8	200	199.89	0.0005	0.11
9	193	190.71	0.0119	2.29
10	174	177.66	0.0211	3.66
11	180	178.19	0.0100	1.81
12	179	180.06	0.0059	1.06
Mean value			**0.0135**	**2.48**

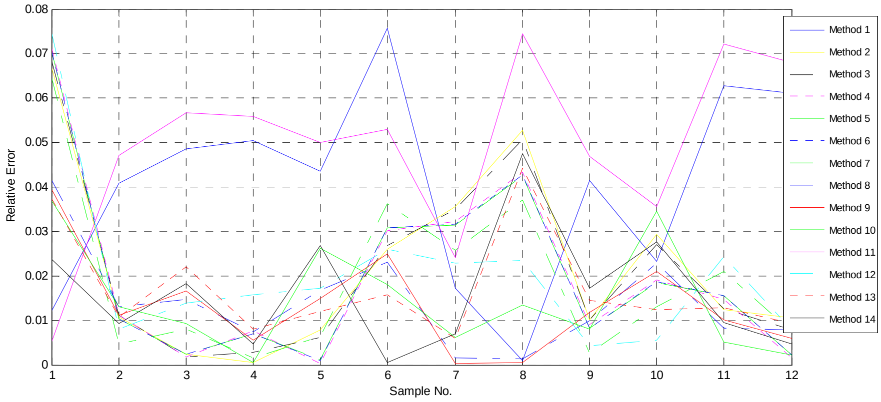

Figure 2. The relative error of asphalt concrete layer thickness measurements calibrated by different methods.

The optimal calibration equation is:

$$\tilde{h}_1 = 0.5c\left(k_5 t_1 + k_6\right) \Big/ \left(\frac{1+\left(k_3\lambda + k_4\right)}{1-\left(k_3\lambda + k_4\right)} \right) . \quad (8)$$

This equation has well-defined physical significance revealing that the time delay and the amplitudes of the received signals that are both critical quantities to be rectified properly.

7. CONCLUSIONS

Based on the layer-stripping inversion, this paper presents 12 kinds of thickness calibration methods for GPR measurement and selects the optimal method that yields a minimum mean relative error. The optimal approach, in which curve fitting of the reflected signals is unnecessary, makes use of four calibrating factors that can be determined through non-linear regression analysis. The calibration was effective and it met the needs of quality assessment very well. The algorithm was successfully applied in the processing of GPR data collected from every scanned point on an 80-kilometre expressway. The methodology of this study may be useful to find the best thickness calibration method for the other layers of asphalt pavement, or other types of pavement structure, although only the systematic error can be effectively diminished through the methods.

8. REFERENCES

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