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RELIABILITY OF GPR DATA INTERPRETATION METHODS FOR DETERMINING THE THICKNESS OF ASPHALT LAYER

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Abstract

Ground penetrating radar (GPR) is mainly used in pavement engineering to determine the thickness of pavement layers. The accuracy of layer thicknesses determined from GPR data depends largely on the accuracy of the dielectric properties of the construction materials used for interpretation. Different GPR data interpretation methods that use the GPR reflected signal to estimate the dielectric properties of construction materials have been developed. The most used methods are using data from the literature, known height method, common midpoint method, wide-angle reflection and refraction method and surface reflection method. Each of these methods has its own benefits and drawbacks. The objective of this study was to evaluate the accuracy of asphalt layer thickness determined by the surface reflection method and the known height method. Data collection was performed using a survey vehicle equipped with a GPR system with 1 GHz air-coupled antenna. The GPR survey was carried out in seven measurement lines and a core was extracted from the pavement in each line. Thickness data from the core was used to determine the dielectric properties of the asphalt layer and to evaluate the reliability of interpretation methods.

Keywords: ground penetrating radar, asphalt layer thickness, dielectric permittivity, surface reflection method, known height method

1 Introduction

Ground penetrating radar (GPR) is a non-destructive testing (NDT) technique that uses electromagnetic (EM) waves to create images of the subsurface [1, 2]. Due to its strengths, mainly related to the possibility of non-contact data acquisition at high speed and to the reliability of measurements, the GPR technique was adopted in pavement engineering in the 1990s [1, 3]. One of the first and still most common GPR application in pavement engineering is the estimation of pavement layer thickness [1-4].

The basic theory behind estimating pavement layer thickness is quite simple. GPR systems transmit short electromagnetic pulses into a pavement and when the pulse encounters a material interface of sufficiently different EM properties, some of the energy will be reflected while the rest will proceed forwards. The reflected energy is collected and displayed as a waveform showing amplitudes and time elapsed between wave transmission and reflection [5, 6]. The propagation and reflection of the radar pulses is controlled by the electrical properties of the materials and the most important electrical property affecting GPR survey results is dielectric permittivity.

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If the dielectric permittivity of the material is known, the EM wave propagation velocity in the material can be calculated, and this allows the thickness of pavement layer to be estimated [5]. Thus, the errors in layer thickness estimation can be related to uncertainties in determining dielectric permittivity [4].

According to [1] the most common methods for determining the dielectric permittivity of pavement materials are using data taken from the literature, known hight method (KHM), common midpoint method (CMP), wide-angle reflection and refraction method (WARR) and surface reflection method (SRM). To date, extensive research has been carried out to evaluate the accuracy of pavement asphalt layer thickness determined using one of the above-mentioned methods. The reliability of the method depends mainly on the characteristics of the site surveyed such as asphalt layer thickness, pavement age and condition, layers homogeneity but also on GPR system used and experience of GPR personnel [1, 2, 4, 7, 8].

The KHM and SRM methods are the most used methods for estimating pavement layer thickness from GPR data generated with an air-coupled antenna. Both methods have their own advantages and disadvantages. The KHM method requires calibration on the cores and the accuracy of the method is highly dependent on the number of cores extracted from the pavement. The SRM is completely non-destructive method, and the accuracy is correlated to the data collection gain which depends on how reflective the pavement surface is [7].

This paper presents a case study of the GPR survey performed on the apron of Pula Airport in Croatia. The focus of the study was to evaluate the accuracy of asphalt layer thicknesses estimated from GPR data interpreted using KHM and SRM methods and to assess the reliability of the interpretation methods used.

2 Data acquisition

The GPR survey was carried out on the apron of Pula Airport in Croatia. The apron pavement consists of unbound base course and asphalt layers. In some sections, the asphalt layers were more than 30 years old. The surface of the pavement was in very poor condition with visible cracks in all directions.

Equipment used for the survey was GSSI GPR system with SIR-20 central unit and air-coupled antenna with central frequency of 1.0 GHz. The longitudinal distance was recorded by a distance measuring instrument. GPR scans were collected every 0.1 m (10 scans/m) with 512 samples per scan. During the survey, the speed of GPR data acquisition was approximately 40 km/h.

The survey was carried out in seven five meters long lines and a core was extracted from the pavement at each line. A metal sheet with a width of 10 cm and a length of 150 cm was placed at the beginning of the survey line to mark the exact position of the start of the survey.

For core calibration GPR data was acquired stationary. During the stationary GPR data acquisition, the pavement surface was marked directly under the antenna for the core drilling. The position of the core in survey line was determined by measuring the distance from the metal sheet to the core marker. After the GPR survey, the cores were taken and for each core the thickness of the asphalt layer was measured at three positions approximately 120° apart along the circumference and the mean value was calculated. The values obtained correspond to the thickness of the asphalt layers, which was used to evaluate the accuracy of the GPR thickness estimation and the reliability of the interpretation methods. Fig. 1. shows example of core marker on pavement surface and extracted core.

For metal plate calibration dynamic calibration was performed over a large metal plate. This enabled for the measurement of a total reflection over a full range of antenna positions that may occur during GPR data acquisition.

Figure 1 Core marker and extracted core

3 Data interpretation

To evaluate the accuracy of the asphalt layer thickness estimation and the reliability of the interpretation methods, the collected GPR data was process and interpreted using RADAN 6.6 software. The GPR data was processed by combining the raw GPR data collected in survey line with the calibration data collected over the metal plate. The interface between asphalt layer and unbound granular layer was determined by manually controlled semiautomatic interpretation based on finding the nearest peak. Estimation of asphalt layer thickness from GPR data is based on the equation [1]:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{1}$$

where v is velocity of EM wave propagation in the asphalt layer, c is the speed of light in a vacuum ($3*10^8$ m/s), ε_r is the dielectric constant of asphalt layer material. When the dielectric constant of asphalt layer material is known by measuring two-way travel time (t_{twtt}) to the interface between asphalt layer and unbound granular base layer it is possible to estimate the thickness of asphalt layer (h) using equation [7]:

$$h = \frac{c}{\sqrt{\varepsilon_r}} \cdot \frac{t_{twtt}}{2} \tag{2}$$

In this study the dielectric constant of the asphalt layer was determined using the KHM and SRM methods.

3.1 Known hight method

To determine the dielectric constant of layer materials using the KHM it is necessary to know the thickness of subject layer in one or more points. This method is usually used for man-made structures (e.g. roads, bridge decks, airport maneuvering areas). The layer thickness is determined on extracted cores at predefined positions. The positions from which cores are extracted must be accurately identifiable in the GPR data. The thickness determined on cores are compared with those in the GPR data to calculate the velocity of the EM waves, i.e. to determine the dielectric constant of the layer material [9]. The main disadvantage of this method is that it is destructive, requires traffic closure and does not account for the possible heterogeneity of the layer along the road [7]. In this study, the dielectric constant of the asphalt layer determined by KHM is calculated using Eq. (2). At each survey line, the thickness of the asphalt layer was measured on core and the two-way travel time was determined from the GPR data recorded during the stationary measurement as the mean value of 100 scans. The stationary GPR data taken at the core locations were analysed by the same software and the same procedure as the other GPR data. Obtained value of the dielectric constant was then used to interpret GPR data in the respective survey line.

3.2 Surface reflection method

By SRM the dielectric constant of layer materials is determined based on the amplitudes of the reflected pulses collected by air-coupled GPR system. The velocity of the EM waves is estimated by comparing amplitude of the waves reflected by the pavement surface with the amplitude of the waves reflected by a metal plate positioned on the pavement surface [1]. The principle of using GPR reflections to compute the dielectric constant is explained in [8]. According to SRM the dielectric constant of the first layer can be estimated based on equation [5, 7]:

$$\epsilon_r = \left(\frac{1 + \frac{A_0}{A_m}}{1 - \frac{A_0}{A_m}} \right)^2 \tag{3}$$

where A_0 is the amplitude of surface reflection and A_m is the amplitude of reflection from metal plate. This approach provides practical advantages as it is complete non-destructive technique that does not require traffic closure [7].

In this study, using RADAN 6.6 software for the analysis of the acquired GPR data the dielectric constant of the asphalt layer material by SRM is estimated by calibration with metal plate. After interpretating the interface between the asphalt layer and the unbound granular layer, the dielectric constant and thickness of asphalt layer are calculated within the software based on Eq. (3) and Eq. (2) respectively.

4 Results and discussion

The results of the asphalt layer thickness measured on the cores and estimated from the GPR data at core locations using KHM and SRM interpretation methods are shown in Table 1.

Table 1 Asphalt layer thickness at core locations.

GPR survey line	Asphalt layer thickness [mm]		
	CORE	**KHM**	**SRM**
SL 1	130	128	126
SL 2	120	118	120
SL 3	235	231	240
SL 4	155	153	142
SL 5	185	185	194
SL 6	160	168	161
SL 7	230	236	259

A deterministic relationship between the asphalt layer thicknesses estimated from GPR data and measured on cores is investigated through linear regression model [7] as shown on Fig. 2.

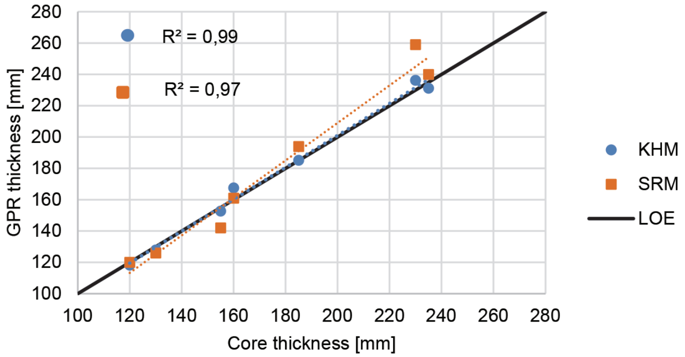

Figure 2 Correlation between asphalt layer thicknesses measured on cores and those estimated from GPR data

For both interpretation methods R-square is higher than 0.95. Considering the specific analyses, asphalt layer thickness values obtained by KHM are closer to the line of equality (LOE) and have higher R-square value indicating a higher reliability of the interpretation method. To evaluate the accuracy of the interpretation methods used, the absolute deviations (Dev.) and percentage errors (Error) were calculated as follows:

$$Dev. = \left| h_{GPR,\, ij} - h_{Core,i} \right| \tag{4}$$

and

$$Error = \frac{\left| h_{GPR,ij} - h_{Core,i} \right|}{h_{Core,i}} \cdot 100\ [\%] \tag{5}$$

where $h_{GPR,i}$ is the thickness on the i^{th} core estimated from GPR data by method j (SRM or KHM) and $h_{Core,i}$ is the thickness measured on the i^{th} core.

The absolute deviations and percentage errors of the asphalt layer thickness determined for the GPR data interpreted using the KHM and SRM methods are shown in Table 2.

Table 2 Absolute deviation and percentage error for asphalt layer thickness for KHM and SRM methods

GPR survey line	**Interpretation method**			
	KHM		**SRM**	
	Dev. [mm]	**Error [%]**	**Dev. [mm]**	**Error [%]**
SL 1	2	1.6	4	3.1
SL 2	2	1.5	0	0.0
SL 3	4	1.6	5	2.1
SL 4	2	1.5	13	8.4
SL 5	0	0.0	9	4.9
SL 6	8	4.7	1	0.6
SL 7	6	2.7	29	12.6
Mean	**3.4**	**2.0**	**8.7**	**4.5**

The highest values of absolute deviation and percentage error obtained for the SRM were 29 mm and 12.6%, while for the KHM the highest values were 8 mm and 4.7%, respectively. The lowest values of absolute deviation and percentage error obtained for both interpretation methods were 0. The mean values of absolute percentage error for KHM and SRM methods were 2% and 4.5%, respectively. Based on the values of the absolute deviation and the percentage error, the KHM interpretation method results in a higher accuracy of the asphalt layer thickness.

To investigate the significance of the asphalt layer thickness differences, the paired samples t-test at significance level α = 0.05 was performed in Microsoft Excel. The thickness estimated using KHM or SRM interpretation method are compared against the thickness measured on core. The basic assumptions were that the samples are paired, the sample differences can be viewed as random, and the distribution of the differences is approximately normal. The null hypothesis is that the mean of thicknesses measured on core is equal to the mean of thicknesses estimated by one of methods used. The alternative hypothesis is that the two sample means are not equal. The paired samples t-test statistics for both interpretation methods are shown in Table 3.

Table 3 Paired samples t-test statistics

Paired samples t-test statistics	**Interpretation method**	
	KHM	**SRM**
t-value	-0.338	-0.779
p-value (two-tail)	0.746	0.465
t-critical value (two-tail)	2.447	

For both interpretation methods, the p-value is higher than the significance level (0.05) and the t-value obtained is smaller than the t-critical value. Based on these two parameters, the null hypothesis cannot be rejected. Thus, at a confidence level of 95% the differences between the thicknesses estimated using KHM or SRM interpretation methods and reference thicknesses measured on cores are not significant.

5 Conclusions

The aim of the presented study was to evaluate accuracy and reliability of different GPR interpretation methods used to estimate the thickness of the asphalt layer. For this purpose, a GPR survey was conducted using an air-coupled 1 GHz antenna in seven survey lines and in each line, core was extracted.

Two methods used to determine dielectric constant of asphalt layer material, i.e. the known height method and the surface reflection method, were considered. Asphalt layer thicknesses estimated by both methods were compared to thicknesses measured on core. Higher values of absolute percentage error were obtained for data determined using surface reflection method. The mean values of the absolute percentage error for the known height method and the surface reflection method were 2% and 4.5%, respectively. A deterministic relationship between the asphalt layer thicknesses estimated from GPR data and measured on cores shows a better correlation for the values obtained with the known height method, indicating a higher reliability of the method. The paired samples t-test statistic shows that at a confidence level of 95% for both interpretation methods, the differences between the GPR estimated thicknesses and the thicknesses measured on cores are not significant.

This study has shown that the GPR system provides a reliable estimate of asphalt layer thickness for both interpretation methods considered.

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