Determining Asphalt Thickness Using Ground Penetrating Radar - A Comparison of Automated and Manual Methods Using Falling Weight Deflectometer Back-calculation Error Correction

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ABSTRACT: The objective of this work was to evaluate and enhance the accuracy of GPR-based pavement thickness evaluations. GPR (Ground Penetrating Radar) data were analyzed to determine asphalt thickness using both a traditional processing method with a trained interpreter, and by automated processing requiring limited operator interaction. It was found that the use of automated GPR processing significantly decreases the amount of time and the expertise needed to analyze the pavement structure, while providing acceptable accuracy in the estimation of pavement thickness. Since incorrect layer identification is a source of GPR analysis error, results of Falling Weight Deflectometer (FWD) back-calculations were used where the layer identification was suspect, and to suggest alternative layer selections. The manual and automated processing techniques were applied to field GPR data collected from 130 FWD test locations at 26 pavement sites throughout Montana. Implementation of the error detection and correction procedure reduced the deviation between GPR and core data by over 30% for both manual and automated methods. Based on data from 130 cores, the average deviation between GPR data and core data was found to be 6.2% (0.32 inches) for the manual method vs. 7.6% (0.42 inches) for the automated method.

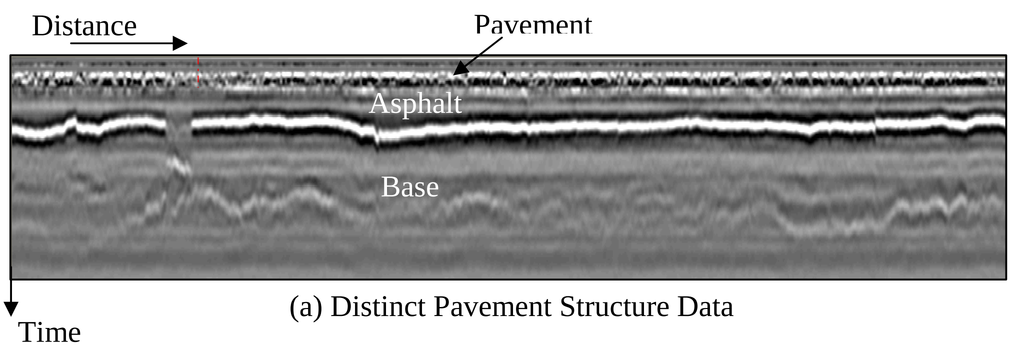
KEY WORDS: Ground penetrating radar (GPR), Automated detection, Pavement thickness, Falling weight deflectometer (FWD)

1 INTRODUCTION

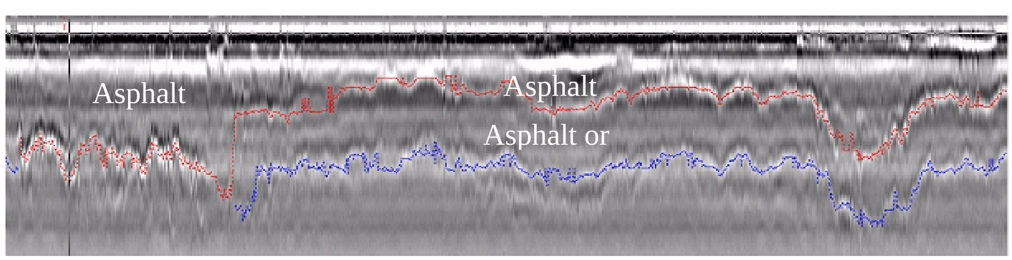
Many pavement evaluation studies rely on as-built construction plans and cores to estimate pavement layer thickness. Falling Weight Deflectometer (FWD) analysis, for example, is particularly reliant on thickness estimates to obtain accurate modulus data. Calculation of pavement remaining life also relies on estimates of current pavement thickness. Reliance on as-built plans for this thickness data, however, can introduce errors since plans can be inaccurate or outdated. Cores can provide this thickness information,, but coring is destructive, expensive and, where pavement varies, core data may not be representative. Ground Penetrating Radar (GPR) can significantly improve the estimation of pavement structure over data obtained from "as built" plans. A detailed review of 45 documented studies shows that GPR pavement thickness measurements typically fall within 2-10% of core values for the bound layers (Maser and Puccinelli, 2009). The specific objective of the work reported herein has been to evaluate the accuracy of GPR-based pavement thickness evaluations at FWD test locations, and to develop a method for improving this accuracy. This evaluation includes a comparison of an automated GPR data processing procedure to a traditional GPR data analysis carried out by a trained operator. In addition, since small errors in estimated asphalt thickness can result in large errors in back-calculated moduli of the asphalt and base layer, unrealistic moduli obtained at the FWD locations can be used as a check of layer type identification (Briggs et. al., 1991, Maser et. al., 2009).

GPR transmits pulses that are reflected and refracted at pavement layer boundaries. The amplitude of the reflected waveforms sent back to the receiver are greater where the dielectric properties of the materials at these boundaries is most different. Typically a GPR analyst will review these images and select or "pick" the layers of interest using a computer program that is able to "track" these high and low amplitude values. Figure 1 shows examples of GPR grey scale "B-scans". In figure 1(a), the asphalt/base interface is clearly distinguished by high amplitude reflections, whereas figure 1(b) shows an area where the layer boundaries, which have been picked, are less distinct. Here the dielectric properties of adjacent layers are more similar, hence the reflected amplitudes are weaker, and interpretation of the roadway structure is more problematic.

FWD testing of asphalt pavement captures the deflection of the surface due to an impulse load striking the pavement through a circular plate. Testing is normally performed to determine the layer moduli and in-situ structural capacity of a pavement. Back-calculation of layer moduli from FWD data requires knowledge of the pavement layer thickness.



(a) Distinct Pavement Structure Data



(b) Pavement Structure Data with Unclear Layer Interpretation

Figure 1: Grayscale image of GPR reflected signal with layers selected.

2 DATA COLLECTION

Pavement thickness data was calculated from GPR surveys at 26 sites in Montana as part of a field data collection program which included GPR and FWD data collection, as well as coring, and auger sampling. As-built pavement layer construction plan data was available for each site. The sites, each 500 feet long, provide a representative sample of pavement structures and environmental conditions found throughout Montana. Five locations at each site were delineated such that GPR and FWD data were collected at the same location. Coring was also performed to provide ground truth at each of the 5 FWD locations.

GPR and FWD data were collected by Montana Department of Transportation (MDT) personnel. The MDT GPR system consists of a GSSI SIR-20 GPR data acquisition unit and laptop, a Model 4105 2.0 GHz horn antenna, along with an integrated FWD. The system was equipped with a DMI (distance measuring instrument) so that the rate of data collection (scans per foot) was controlled. The GPR horn antenna is positioned in front of the vehicle, and the FWD is positioned in the rear. The time range for the 2 GHz antenna was set to 12 nanoseconds which provides the maximum detectable depth of approximately 20 inches. (Maser et. al., 2011)

GPR data was collected during FWD testing in 75-100 foot sections at each FWD test location at a density of 10 scans per foot. The pavement at the FWD load plate was painted to mark the location of the test for cores taken later. GPR data was also collected continuously from the start to end of each site, during separate tests done at 2 and 5 scans per foot. This paper uses both the FWD data files and the continuous data collected at 5 scans per foot.

A metal plate calibration test was carried out at each site for the 2 GHz horn antenna. To perform this test, a metal plate is positioned under the antenna, and the antenna is raised and lowered over the plate by jumping on the front vehicle bumper. The plate calibration files are used for data processing.

3 GPR DATA ANALYSIS METHODOLOGY

3.1 Manual Analysis Method

For the manual method, GPR data was analyzed using RADAN® , a commercial software package provided by the GPR manufacturer. Aside from two calibration cores that were provided from two of the sites, the GPR data analyst had no access to the core data during the analysis process. Further reference to core data in this paper is not part of a proposed methodology, but rather as a means for assessing the accuracy of the methods employed.

A metal plate calibration file is needed to process and calibrate the GPR signal in the radar files. Two methods were used in this study for processing site data with the calibration file. The "Global Plate" method uses the same plate reflection/jump test data for all the sites. The "Custom Plate" method uses a plate reflection/jump test file collected at each individual site. Data processed using the Custom Plate method is used in this study. Processing using RADAN involves the following steps:

- Generate a "horn calibration file" from the jump test data file.
- Visually inspect each file to align reflective marks in the GPR file to section reference. information
- Pre-process the data files with the horn calibration file.
- Visually inspect each processed file to:

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    - select and pick reflections as potential layer boundaries.
    - locate FWD test points in the files.
- Review as-built plans and compare the depth of reported layers with picked layer boundaries.
- Save the layer interpretations and their respective velocity and thickness calculations.
- Extract and calculate the average thickness at each FWD location.

The layer picking step requires some expertise. The GPR file from each site is loaded into the program and appears as an image similar to those seen in Figure 1. The data must then be interpreted. Clearly defined layer boundaries, like the data seen in Figure 1(a), are easily picked as the analyst scrolls through the data in the image. In cases where the data is ambiguous or obscure, picking can be more time consuming as the analyst is forced to erase and re-pick areas where the program has tracked badly, or where interpretation becomes altered.

3.2 Automated GPR Analysis Methodology

Automated GPR data analysis was performed using GPRAP©, which can be run as a module incorporated into the FWD data collection program, or as a macro in Excel. In some configurations, the program is executed directly in the field at the time of data collection. For the purposes of this study the program was run within an Excel spreadsheet. This automated program works with short sections (50 - 100 feet) of GPR data collected along with the FWD testing. Since the GPR antenna is a fixed distance in front of the FWD equipment, the FWD test location is always at a fixed location from the end of each GPR file. Once the filenames are listed in the spreadsheet, a macro is used to cycle through the list of files and the corresponding FWD location in the files, and send this information to the GPRAP program for processing. GPRAP locates the significant layer boundaries in each file, and calculates the layer thicknesses. The algorithm determines, using a layer indicator, which of the layers is the most likely candidate for the bottom of the bound pavement. If multiple layers are detected, the algorithm reports alternative candidate values in the order of their likelihood.

Processing using GPRAP involves the following steps:

- Set up the spreadsheet with the name of the calibration (plate test) file and the parameters to use for processing. The necessary parameters are the plate scan number, size of the analysis window, location of the analysis within the file and the search resolution. In the case of the FWD GPR files, the analysis location was always 23.5 feet before the end of the file.
- Create a list of the GPR filenames and their corresponding calibration (jump test) files.
- Run the GPRAP program which will automatically pick six possible layers and rank them in order of most likely candidates and report the top three candidates.
- Choose the layers to use for FWD analysis from the three candidates returned by GPRAP.

By collecting data at the FWD test locations, the method does not require search and alignment to find FWD locations in the GPR file. This step is often a time consuming process that is also a source of error in the traditional manual GPR method. GPR scanning during FWD data collection assures that the GPR location is keyed directly to the FWD location and thickness will represent the thickness at the exact location as the FWD test location. The method does not require the GPR analyst to pick layers as the automated program delivers the layer alternatives to the user.

3.3 Initial Layer Thickness Results

The GPR layer thickness results generated with the manual and automated methods, and their relationships to the as-built data and core data, are summarized in Table 1. For each site, the plan thickness, the average thickness from the 5 cores, and the average thickness of the 5 FWD locations measured by RADAN and GPRAP was compared (McGrath et. al., 2012). A summary of data from all sites is presented in Table 1. The error (based on core data) in the plan and GPR data is shown in the table. Note that since RADAN data analysis requires some operator judgment, all data was analyzed by the same operator to remove this factor as a variable in the evaluation.

Table 1: Sample of average asphalt thickness error at each site based on plan, RADAN and GPRAP vs. cores.

	Average Asphalt Depth (in)					
	Plan Error		RADAN Error		GPRAP Error	
	inches	%	inches	%	inches	%
overall averages	0.95	15.2%	0.56	9.7%	0.59	10.1%
sites < 8% error	12		21		15	
sites > 20% error	6		4		4	

4 LAYER SELECTION CHECKING

With both manual and automated methods, it is worthwhile to obtain independent verification of layer identification to ensure that the correct layer has been selected for the thickness calculations. As discussed below, this study uses FWD back-calculation results as an independent verification after the layers were picked and the thickness calculations performed. The proposed checking procedure assumes that only GPR and FWD data are available (i.e., no core data).

The GPR layer thickness data generated by the procedures described above was used with the FWD data to back-calculate layer moduli. The program used to perform back-calculation was MODULUS 5.1 developed by the Texas Department of Transportation. MODULUS produces a back-calculated layer moduli and a back-calculation error through an iterative process using a deflection data file and manual inputs including layer thickness. The program was run using the "wide modulus range method" which allowed the program to iterate through an allowable modulus range for surface layers from 100 ksi to 3,000 ksi with a Poisson’s ratio of 0.35. This method was used solely with the intention of allowing unreasonable FWD results to be obtained and is not recommended for normal analysis (Maser et. al. 2011). In this way, unusual model errors and moduli were used as a way of checking the thickness data for suspect values. The layer model used for input into MODULUS, and the details of the backcalculation process are described in Maser et. al., 2011.

Using the back-calculated data, three checks were established as test conditions for possible incorrect GPR asphalt thickness estimates. The first two conditions are met when unreasonable results are obtained by FWD back-calculation, indicated by either a surface modulus > 2400 ksi or large errors in the back-calculated deflection model fit (back-calculation error > 3%). The third condition occurs when the GPR estimate of the asphalt layer thickness differs from the plan drawings by more than 1 inch. When two or more of these conditions are present at a site, the site is flagged for further review. If warranted, an alternative layer generated by the GPR analysis, is selected.

4.1 Manual Method Layer Check

The layer moduli (E) and model error (Abs Err) obtained from the above calculations for the manual method GPR data are shown in Table 2. As seen in Table 2, 4 sites (sites 2, 4, 9 and 24 - highlighted in yellow) were flagged by the selection process for reevaluation.

Upon review of the GPR data, an acceptable alternative layer was selected in 3 of these 4 sites (sites 2, 4 and 24), and FWD calculations were then repeated with the new GPR thickness estimates. The bottom of Table 2 shows the results of the FWD calculations using the alternative layers. For site 9, a review of the GPR data showed no other acceptable layers for selection, so the original selection was kept. The updated FWD back-calculated data and check results for sites 2, 4 and 24 are designated in Table 2 as site numbers "02 (2)", "04 (2)" and "24 (2)" respectively.

4.2 Automated Method Layer Check

Layer selection in the automated method uses the same criteria as the manual method to test for incorrect GPR thickness estimates of the surface layer. The moduli (E) and model error (Abs Err) obtained from these calculations were tabulated. Three sites were flagged by the selection process for reevaluation. The GPRAP layer results provided no acceptable alternative selection for one site. The other two sites had a deeper alternative available and were corrected.

Table 2: Sample of test criteria for possible layer thickness errors - manual method.

Site #	Back-calculated Data			Check Criteria			
	E (ksi)	Abs Err (%)	GPR - plan	E (ksi)> 2400	GPR-Plan (in.) >1.0	Abs Err (%) >3	Check?
01	1186	1.2	3.78		True		OK
02	2804	4.8	0.70	True		True	check
03	988	2.3	0.14				OK
04	3000	8.3	-1.08	True	True	True	check
02 (2)	1045	1.9	3.40		True		OK
04 (2)	905	1.1	2.09		True		OK

5 REVISED RESULTS AFTER LAYER CORRECTIONS

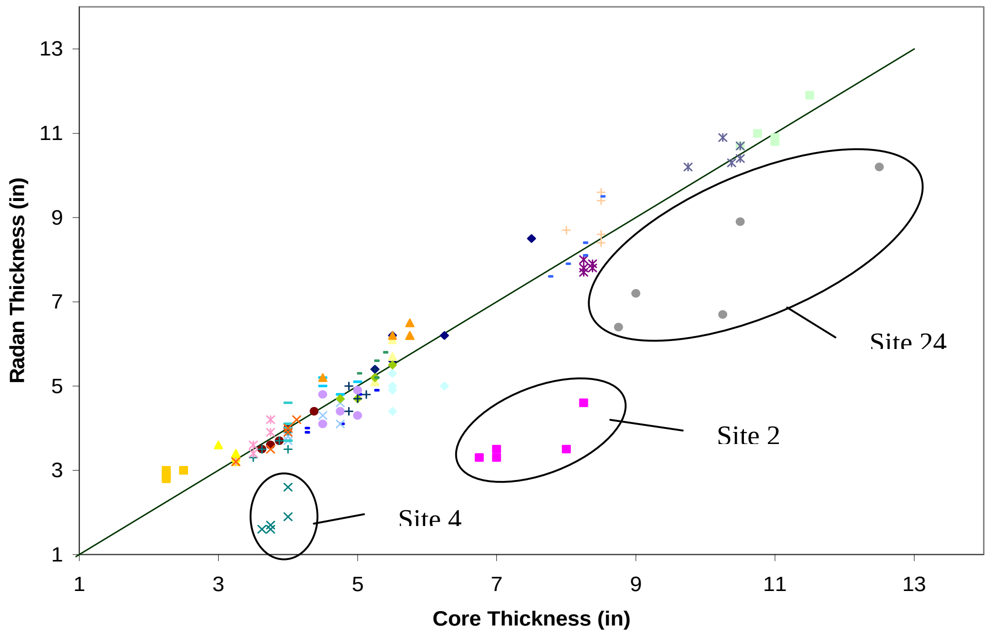
Table 3 repeats the results of Table 1, showing GPR layer thickness showing summary results for all sites after the revisions described in the layer checking process above. The cells highlighted in yellow are those that were modified as a result of the checking process. Figure 4 illustrates the site-by-site result of the correction process.. This figure plots the GPR vs. core thickness for each of the 130 test locations using the manual GPR method. Figure 3(a) shows the results before the correction. Figure 3(b) shows the comparison of manual GPR thickness estimates compared with cores taken at the same locations, after changing the selected layer for sites 2, 4 and 24.

Table 3: Sample of average asphalt thickness error at each site based on plan, RADAN and GPRAP vs. cores (after correction).

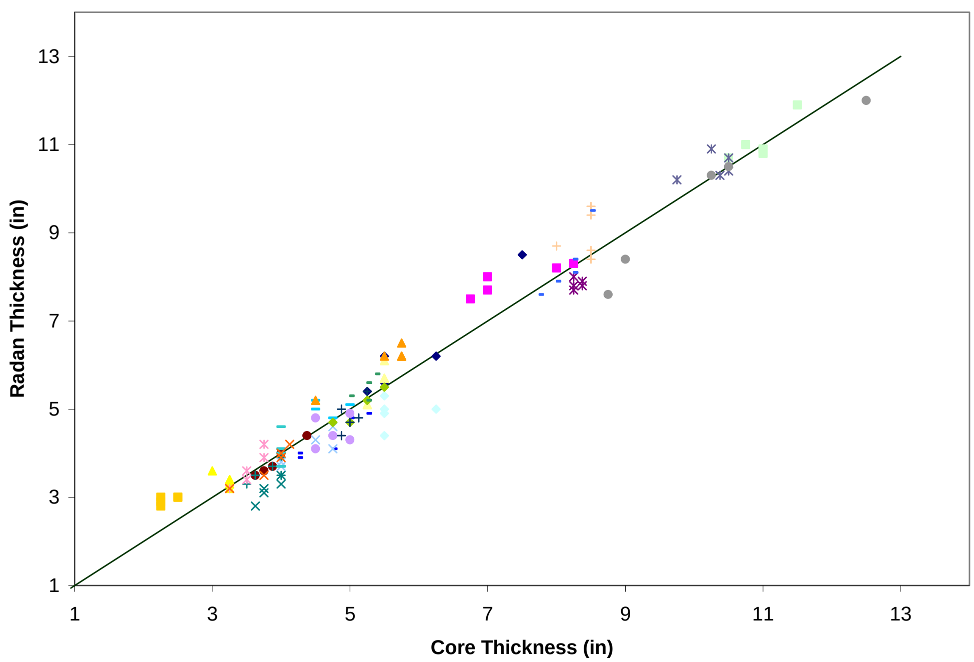
	Average Asphalt Depth (in)					
	Plan Error		RADAN Error		GPRAP Error	
	inches	%	inches	%	inches	%
overall averages	0.95	15.2%	0.32	6.2%	0.42	7.6%
sites < 8% error	12		23		17	
sites > 20% error	6		1		2	

At these sites, the layer structure in the GPR data was unclear, and consequently the layer boundaries initially selected were guided in part by information from as-built plans. The data from all three of these sites plots well below the y=x curve in figure 3(a). This means that the layer thickness was underestimated by GPR, which agrees with the FWD calculations flag (surface modulus > 2400 ksi). An overly high modulus indicates that the layer chosen is possibly too thin. The alternative layers selected for these sites appear to be the correct pavement/base boundary - as shown in the plot in Figure 3(b).

Once the criteria checks indicated that a possible incorrect thickness estimate had been used, it was a simple matter to choose the next most appropriate layer in the GPR file. The results obtained by correcting the chosen layer lead to a much improved estimate of thickness data. Results obtained from the manual method and the automated method produce very similar results.



(a) Before Correction



(b) After Correction

Figure 3: GPR asphalt thickness at each location using RADAN vs. core thickness.

6 DISCUSSION OF RESULTS

Table 4 summarizes the overall comparison of manual and automated GPR analysis results vs. core and plan data both before and after the correction process.

Table 4: Average asphalt thickness error before and after correction.

METHOD	CORRECTION	ASPHALT THICKNESS ERROR (%)		ASPHALT THICKNESS ERROR (IN.)	
		PLAN	GPR	PLAN	GPR
Manual	before	15.2%	9.7%	0.95	0.56
Automated	before	15.2%	10.0%	0.95	0.59
Manual	after	15.2%	6.2%	0.95	0.32
Automated	after	15.2%	7.6%	0.95	0.42

Note that in both the manual and automated cases, the use of the error checking procedure reduced the error by over 30%. It is important to emphasize that this correction process was implemented without the knowledge of core data. Consequently, while some errors in the GPR analysis were effectively corrected, others were not. Nevertheless, the overall accuracy that was obtained was consistent with that reported in prior studies (Maser and Puccinelli, 2009).

Another important observation is that the average automated analysis error of 7.6%, while slightly greater that the manual analysis error, is significantly more accurate than the plan data, and in a range that would be considered acceptable for pavement evaluation studies. The average corrected GPR thickness estimates for both the manual and automated methods are less than 1/2 inch. Previous work has shown that the increased accuracy provided by such data can lead to more accurate rehabilitation designs (Maser et. al., 2011).

Note that the numerical threshold values for the check criteria shown in Table 2 are somewhat arbitrary, and might require adjustment for other pavement types under other conditions. Further research into the use of these criteria could ultimately lead to a more robust set of thresholds.

7 CONCLUSIONS

The work described in this paper has demonstrated the accuracy that can be obtained using GPR data for determining pavement layer thickness. This work is based on a test program carried out at 26, 500-foot long sites representing all climatic regions of Montana. The testing included GPR measurements of pavement layer thickness, FWD measurements at 5 locations within each site, and core and auger measurements to directly determine layer thickness at the FWD locations.

The GPR data was analyzed using both manual and automated methods, and the results were correlated with the core layer thickness data to assess the accuracy of each method. The initial analysis of the GPR data showed the average absolute asphalt thickness error when compared to cores to be within 9.7% for the manual method, and 10% for the automated method. For reference, the error in the as-built plan thickness data is 15.2%.

A checking procedure was successfully implemented, based on FWD back-calculation data computed using the GPR thickness, leading to the identification and correction of layer identification errors. Implementation of this procedure reduced the GPR thickness error for the manual and automated methods to 6.2% and 7.6%, respectively. Although the automated GPR procedure is slightly less accurate than the manual method, it still produces more accurate results than the plan data. Given the time required for manual analysis, the automated method may be preferable in conjunction with FWD data collection.

8 ACKNOWLEDGEMENTS

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