

Evaluation of Technologies for Nondestructively Determining Concrete Pavement Thickness

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Abstract

The U.S. Army Engineer Research and Development Center (ERDC) was tasked by the U.S. Air Force (USAF) to evaluate the capability of emerging nondestructive testing equipment to accurately estimate the thickness of pavement surfaces without requiring large footprint equipment or pavement repairs. The ERDC research team conducted an evaluation of eleven nondestructive technologies, including eight ground penetrating radar devices and three different seismic technologies, on nineteen concrete test locations with varying pavement thicknesses. For each of the different pavement types, a single core was extracted to provide calibration points. The involved vendors and researchers estimated initial thickness, and upon receiving the calibration core thicknesses, final thickness estimates were computed. The accuracy of each technology was quantified by calculating the absolute difference between the actual core measurement and the estimated measurement. This paper describes the eleven different technologies, their performance on the test locations, and comparisons in terms of accuracy and implementation difficulty.

Introduction

The U.S. Army Engineer Research and Development Center (ERDC) was tasked by the U.S. Air Force (USAF) to evaluate the capability of emerging nondestructive testing equipment to accurately estimate the thickness of pavement surfaces without requiring large footprint equipment or pavement repairs. The USAF is tasked with operating anywhere in the world in support of the nation's objectives. To support deployments, the performance capabilities of potential airfields must be evaluated quickly and accurately. The assessment of pavement thickness is fundamental in pavement condition evaluation. The Airfield Pavement Evaluation (APE) team of the USAF is tasked with deploying to airfields of interest, often with minimal resources, to rapidly evaluate the condition and structural capacity of the airfield pavement infrastructure. Currently, the APE team must core the pavement to determine the pavement thickness. Coring is a destructive data collection method that requires bulky equipment, a water source, and patching materials to repair the hole in the pavement.

The ERDC research team conducted an evaluation of eleven nondestructive technologies, including eight ground penetrating radar devices and three different seismic technologies, on nineteen Portland cement concrete (PCC) test locations with varying pavement thicknesses. For each of the different pavement types, a single core was extracted to provide vendors/researchers with calibration points. Vendors and researchers provided initial thickness estimates based on the results of testing with their respective technologies; and then after receiving the actual core thicknesses for calibration, they provided final thickness estimates based on post calibration testing. Devices were evaluated in terms of accuracy and implementation difficulty.

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The research significance of this project is the side-by-side comparison of multiple devices that provide nondestructive alternatives to coring of pavement. The pavement surface thickness is a critical component of the data needed to accurately assess the structural capacity of the pavement.

Ground Penetrating Radar Technology

Since the 1970s, ground penetrating radar (GPR) has proven to be a valuable tool for applications such as the evaluation of highways, railroad tracks, and bridge decks. GPR has been used to locate pavement layer interfaces, buried utilities, voids, and items such as rebar within concrete. There are two major types of GPR, the air-coupled system and the ground-coupled system. Air-coupled systems are mounted off of the ground so that they can rapidly collect data, and they can often move at highway speeds. They are often higher frequency (1 GHz or higher) and can collect high-resolution data. However, the depth of penetration is normally limited because of the high frequency. Ground-coupled systems are placed on the ground and require either manually moving the device or a cart to move the system along the pavement. These systems collect data at a much slower rate, but normally have a deeper penetration depth, because they are often equipped with lower frequency antennas (< 1 GHz).

To determine the pavement thickness for pulsed systems (air-coupled or ground-coupled), a short electromagnetic pulse is transmitted into the pavement. When the electromagnetic wave encounters an interface with a dielectric discontinuity, the electromagnetic wave is partially reflected back to the receiving antenna. The relationships between the layer thicknesses, dielectric constants, and the reflection amplitudes have been described by Scullion et al. (1994). A limitation of the ground-coupled antenna method is that dielectric constants cannot be estimated from the collected data. Dielectric constants must be assumed from average values or calculated using calibration cores. Air-coupled systems provide estimated dielectric values based on data collected. Another type of radar that has been recently developed is a step-frequency GPR. Rather than using just one frequency as with the pulsed radar methods described above, this type of GPR uses a range of frequencies.

GPR has many advantages and disadvantages when used to evaluate pavement thicknesses. The following items should be considered, prior to using GPR:

- Only pavement layers with a difference in dielectric constants can be detected. If the dielectric constants are too similar, no distinction can be made between layers, leading to incorrect thicknesses.
- GPR is often not used because automated software or processing has not advanced enough to be reliable for routine use, and manually processing GPR data can be time-consuming (Lahouar and Al-Qadi 2008). A trained, experienced user is normally required to process GPR data.
- Higher frequency GPR systems yield better resolution data but are limited in penetration depth. Lower frequency GPR systems can penetrate deeper, but are limited in resolution.
- Concrete, especially newly constructed concrete, attenuates the GPR signal and reduces the penetration depth (Halabe et al. 1993). Freshly placed concrete has high free water and dissolved salt content that result in high attenuation of the GPR signal in concrete. The free water content decreases as the concrete cures over time (De Souza et al. 2004).

For this study, five ground-coupled systems, two air-coupled systems, and one step-frequency system were evaluated. Ground-coupled antennas with frequencies ranging from 800 MHz to 2.3 GHz were used in this study. For the ground-coupled systems, two were single frequency systems, one was a dual antenna system using a common midpoint method, and two systems consisted of antennas of different frequencies. Data from the systems with different frequency antennas were analyzed separately, and the best estimate was reported. The air-coupled systems were both 1 GHz horn antennas that mounted onto a vehicle but came from different manufacturers. One step-frequency 3D radar system was also tested.

2 GHz ground-coupled GPR. One of the ground-coupled single antenna systems was a 2 GHz GPR antenna with a built-in distance-measuring instrument (DMI) to account for the travel distance of the antenna. The data acquisition system had a wireless connection to a laptop to make data collection easier. Setup of the system was completed in less than 5 min and required only connecting the cable and turning on the laptop. Data acquisition consisted of moving the small GPR antenna by hand across the test location. Data were collected at a rate of 197 scans per meter, and the acquisition time for each test location was approximately 30 seconds.

1.5 GHz ground-coupled GPR. The other ground-coupled single antenna system was a 1.5 GHz ground-coupled antenna attached to a cart equipped with a DMI to assist in the ease of data collection. The controller for the antenna remained in the survey vehicle. Data were collected at a rate of 131 scans per meter, and an electronic trigger was activated as the antenna traveled over the test location. The acquisition time for each test location was approximately 30 seconds.

1.5 GHz dual ground-coupled CMP GPR. Dual 1.5 MHz ground-coupled antennas were used in a common midpoint (CMP) method. This method consisted of the two antennas, controller, a wooden frame to hold the antennas, a plastic sheet to aid in the movement of the antennas, and a DMI. The two antennas were attached to a wooden form that consists of a pulley system that controls the movement of the two antennas so that they are moved equally and opposite from a common initial starting position. One antenna served as the transmitter antenna, and the other served as the receiver antenna. GPR data and distance data are recorded as the antennas move; GPR data were collected every 1 mm. The reflected GPR data resulted in a hyperbolic pattern. It took from two to five minutes to acquire data for a single location using this method. Extensive post-processing was required after the data collection.

1 GHz air-coupled GPR A and B. Two 1 GHz air-coupled horn antennas (systems A and B, respectively), from different manufacturers, were used in this study. Setup of the horn antenna required attaching the antenna on the vehicle and connecting the cables. For the 1 GHz air-coupled GPR A system, the antenna was attached to the rear of the vehicle, and for the 1 GHz air-coupled GPR B system, the antenna was attached to the front of the vehicle. Setup required approximately 30 minutes, but the actual testing of each test point was rapidly executed (< 10 seconds), because all that was required was the horn antenna be driven over the test locations. Test points within an area could be collected during one pass with this system as long as the points were in a straight line. To determine the dielectric constants, a metal plate calibration was completed prior to testing. Additionally, a bounce test to account for the changes in antenna height was completed prior to testing to enhance the data processing later for

the GPR A system. The bounce test consisted of standing on the back of the vehicle and making the antenna bounce. The metal plate calibration and bounce test took approximately 15 minutes. Data are collected as the vehicle is traveling, but data processing is required afterwards. Data were collected at 33 scans per meter of travel for the GPR A system. For the GPR B system, data were collected at a rate of 50 traces per second, but data acquisition is distance driven, so the operator can specify the frequency of data collection. An electronic DMI was mounted to the vehicle to monitor distance as data were collected for both systems.

900 MHz and 1.5 GHz ground-coupled GPR. One of the multi-antenna systems tested consisted of two small, portable ground-coupled GPR antennas (900 MHz and 1.5 GHz). The 900 MHz antenna came with a pole attachment that allows the user to push the system along the pavement test site. The 1.5 GHz GSSI ground-coupled antenna had wheels to assist with moving the antenna along the pavement. Testing took less than 30 seconds per location for both antenna systems. Both sets of data were used to determine thickness. As a general rule, for pavements less than 46-cm thick, the 1.5 GHz antenna was used. If the pavement was thicker than 46 cm, the 900 MHz antenna was used.

800 MHz, 1.2 GHz, 1.6 GHz, and 2.3 GHz ground-coupled GPR. The other multi-antenna system consisted of 4 different ground-coupled GPR antennas with frequencies of 800 MHz, 1.2 GHz, 1.6 GHz, and 2.3 GHz. Set up required approximately 30 minutes and consisted of assembling the utility cart and connecting the cables. The utility cart is a generic cart used to hold antennas of different sizes, the control system, and a laptop for data collection. This cart was easy to take apart and reassemble as needed. Up to four antennas can be put into the cart for simultaneous testing. Only two antennas were used at a time for this study. The time to switch out the antennas was approximately 5 minutes. Once the antennas were in the cart and plugged in, testing was rapid (less than 1 minute), as data were collected as soon as the cart was rolled over the testing location. While all four antennas were tested for this study, the best antennas for this study were the 2.3 GHz antenna for shallow depths, and the 800 MHz antennas for the deeper depths.

3D GPR. The 3D radar system operates in the step-frequency mode and provides three-dimensional data. The system covers a frequency range from 140 MHz to 3 GHz, with a step frequency of 2 MHz. The antenna was 1.8 meters wide and had 21 channels spaced 7.5 cm apart. Setup of the equipment required approximately one hour. Data were collected as the antenna traveled over the test location. High-resolution data were collected during testing, and thus the vehicle had to travel at a slow speed averaging 3 km/h. Data are available in real-time during collection for thickness estimation, but further analysis and processing is required before thickness data can be more accurately determined. Similar to the ground-coupled GPR systems, this system required an estimated dielectric constant because it could not be extracted from the data collected.

Wave Propagation Technologies

Wave propagation methods include those based on sonic, seismic, and vibration methods. These nondestructive methods measure dynamic properties that are related to physical conditions (Olson and Wright 1990).

Impact echo is a type of mechanical wave technique that was first used in 1983 by the National Bureau of Standards (Sansalone 1997). Impact echo methodology involves using an impact source on the surface of the pavement to create low frequency stress waves in the pavement and transducers on the surface of the pavement to measure the reflecting waves from layer interfaces or flaws of the structure imaged. A fast Fourier transform is used to convert the displacement versus time signals to the frequency domain to provide data about flaw location, such as at layer interfaces (Sansalone 1997). It is typically used for nondestructive testing of concrete, because the thickness of concrete pavement is typically sufficient for the measurement range required by mechanical wave measurements. Additionally, the mechanical impedance contrast for concrete pavement and base material is normally strong enough to delineate the layer interface. However, mechanical wave techniques are not as successful in asphalt because of the lower modulus of asphalt, as well as the changes in modulus resulting from changes in temperature (Maser et al. 2006).

Ultrasonic tomographic imaging is another type of mechanical wave based technology that uses sound waves (> 20 KHz) to penetrate pavement and generate images. Early ultrasonic methods were problematic, because they required a coupling liquid and were not able to penetrate sufficiently. A new technology utilizing dry point contact (DPC) transducers has advanced the use of ultrasonic imaging in the civil field. This technology has been used extensively for PCC-related applications, such as for detecting reinforcement, thickness determinations, delaminating detection, and the diagnostics of joints (Hoegh et al. 2011).

Ultrasonic Tomography. The ultrasonic tomography technology tested is able to penetrate concrete and reveal structures or layers in the concrete in real-time. It has been primarily used for concrete imaging applications to nondestructively view objects such as holes, cracks, and reinforcement bars within the concrete. It operates in a frequency range of 20-100 kHz, and at an average frequency of 50 kHz. Near real-time thickness measurements can be obtained with this device. This device consists of 40 transmitting and receiving dry point contact (DPC) transducers on the bottom of the device. There are 45 transmitting and receiving transducer pair measurements that allow for redundancy to confirm measurements when measuring heterogeneous materials such as PCC and asphalt. The device is adaptable to rough surfaces, because each transducer has a wear-resistant ceramic pin and independent spring load. A single measurement takes 3 seconds, and the DPC transducers can measure up to 1 m deep. Testing at each location took approximately 1 minute, because calibration scans were done at every location in addition to five readings for comparison purposes. Calibration, or fine-tuning, was accomplished by a method of measuring the average ultrasound velocity in the pavement and adjusting the gain accordingly. Calibration is not required if testing on similar pavements, but will increase the accuracy of the device, because it measures the velocity of the ultrasonic waves in the material.

MISW. Another wave propagation method used was a multiple impact surface waves (MISW) method. The MISW method estimates the surface wave velocity of layered systems along the depth by using the dispersive characteristics of surface waves. MISW equipment consisted of a measuring tape, instrumented hammer (91 grams), seismic accelerometer, lithium based grease, and a computer. Each test, including the setup of the test, took approximately 10 to 15 minutes. All of the equipment had to be moved from location to location, which increased the total testing time. The

accelerometer was placed on the location of interest with the lithium-based grease to hold it in place, and a measuring tape was stretched to 1.5 m away from the accelerometer. The hammer was used to tap the pavement four times every 5 cm. The first tap was a seating tap, and the last three taps were averaged. The hammer was instrumented to trigger data acquisition. The accelerometer measured the Rayleigh waves (surface waves) propagating through the concrete. Data processing involved the determination of the variation of the surface wave velocity with depth by using the dispersive characteristics of surface waves (Olson et al 2010). Since the MISW method can estimate the surface wave velocity of the material by using the surface wave measurement, it should require less correction via the calibration cores. A limitation of MISW is the presence of cracks in the pavement. Surface waves do not propagate through them, so care should be taken to place the entire setup on pavement without significant cracks.

Impact Echo. An impact echo device was also tested. The device consisted of a piezoelectric transducer with an impactor or impulse hammer. The impactor or impulse hammer (113 grams) induces vibration in the pavement, which is reflected back to the receiver of the device. The built-in impactor was used for pavements with thicknesses 10 to 61 cm. The small hammer was used for pavements 30- to 91-cm-thick. The reflected wave test data were collected in the time domain and underwent a Fast Fourier Transform to extract the frequency peaks. Setup required less than 5 minutes, because all that was required was for the computer to be turned on and the cables to be connected. Data acquisition took approximately 1 minute per test location. Thickness estimates are displayed immediately after data acquisition. If the thickness of the pavement is unknown, the compression wave velocity is given an estimate that is typical of pavement material being tested. Once calibration cores were provided, the compression wave velocity could be determined for each pavement type. The impact echo method can be limited for pavements less than 8-cm.-thick.

Testing

Devices were evaluated at three different sites at the ERDC, Vicksburg. The first site was located at the Poor House Test Area, where a custom test section was constructed with varying thicknesses of AC and PCC. The second site selected was the Forest Service Road Test Area, which was constructed in 1988 for traffic testing purposes, but had a newer test section constructed for testing flowable fill pavement repairs. The last site used a previously tested section constructed for a project to determine minimum PCC thickness for airfield pavement design, and this site was located in Hangar 4.

The test points and their layer thicknesses are listed in Table 1. These test points are part of a larger study that included asphalt test data as well, so the data points shown are not numbered sequentially. All test points with similar properties also had a calibration point associated with them. Once vendors provided their initial thickness estimate, they were given the calibration points to use, if necessary.

Data were collected for each technology at each of the test locations. Test locations were marked with a 10-cm circle to indicate where a 10-cm core would be extracted after the conclusion of testing (Figure 1). For GPR testing, metallic tape was put on the pavement 61 cm from to the center of the circle. This metallic tape can be seen in the GPR signal and enables the user to locate test points.

Table 1. Thicknesses of test points.

Test Number	Site	PCC Layer 1 (measured from extracted cores)	Layer 2 (construction data)
11 ^{cal}	Custom Test Section	21.38 cm	15.2 cm limestone
12	Custom Test Section	63.39 cm	15.2 cm limestone
13	Custom Test Section	63.29 cm	15.2 cm limestone
14	Custom Test Section	62.55 cm	15.2 cm limestone
15	Custom Test Section	37.89 cm	15.2 cm limestone
16	Custom Test Section	37.99 cm	15.2 cm limestone
17	Custom Test Section	39.37 cm	15.2 cm limestone
18	Custom Test Section	19.16 cm	15.2 cm limestone
19	Custom Test Section	20.32 cm	15.2 cm limestone
20	Custom Test Section	21.17 cm	15.2 cm limestone
32	Forest Service Road	19.90 cm	76.2 cm flowable fill
33	Forest Service Road	12.07 cm	76.2 cm flowable fill
34 ^{cal}	Forest Service Road	22.33 cm	76.2 cm flowable fill
35	Forest Service Road	32.28 cm	30.5 cm compacted well-graded gravel
36	Forest Service Road	19.69 cm	30.5 cm compacted well-graded gravel
37	Hangar Test Section	26.67 cm	33.0 cm limestone
38	Hangar Test Section	26.35 cm	33.0 cm limestone
39	Hangar Test Section	28.47 cm	33.0 cm limestone
40 ^{cal}	Hangar Test Section	22.65 cm	45.7 cm limestone
^{cal} Calibration test point			



Figure 1. Test location marked with a circle to indicate location of the core hole and metallic tape spaced 61 cm away from the center of the core hole.

Results and Discussion

For this evaluation, the comparisons were focused on only the top pavement layer. For each of the devices, three values were computed to evaluate the accuracy. The difference error was calculated as the absolute difference between the predicted thickness measurement from the device and the actual core thickness measurement. The average of these differences was calculated for all of the test locations and was used as the main value to evaluate accuracy of the devices. The coefficient of

determination, R^2 , for each device for all the test locations was reported as a measure of how well the measured data linearly correlated to the actual core thicknesses. Additionally, because the percent error is often what is reported in literature, it was also calculated and included so that these devices could be compared to the performance of those listed in literature. Because it is difficult to determine the actual thickness difference with the percent error, it was not used as the main measure of accuracy. For a given thickness difference, thicker pavement test locations have smaller percent errors than for thinner pavements. The percentage of test locations measured was also computed. The number is crucial, because the device may have provided data with favorable error values, but the device is beneficial only if the majority of the data was collected. These values are listed in Table 2 and ordered by the average difference error. For all devices tested, the predicted values plotted with the actual core thicknesses can be found in Figures 2 – 8.

Vendors and researchers for all devices, except for the ultrasonic tomography device, provided both initial results and results after calibration upon receiving the selected core thicknesses. Error values were also computed for the calibrated data and are listed in Table 2.

Four of the devices performed well on the PCC test locations. These devices had an average difference error that was 1.5 cm or less, a coefficient of determination value of 0.9 or higher, and a percent error of 7% or less. Some of these devices performed well only upon calibration, and some performed well without calibration.

Table 2. Average difference error, R^2 values, percent error, and percentage of test locations measured for the devices tested.

Device	Average Difference Error ^a (cm)	R^2 value ^b	% Error ^c	% Test Locations Measured ^d
Corrected, Calibrated Impact Echo ^e	0.82	1.00	2.07%	95%
Calibrated MISW	0.86	1.00	2.35%	53%
Ultrasonic Tomography	1.09	0.99	4.28%	100%
Corrected Impact Echo	1.13	0.99	3.87%	95%
Calibrated 1 GHz Air-Coupled GPR A	1.30	0.93	6.14%	42%
MISW ^f	1.47	0.99	4.19%	53%
1 GHz Air-Coupled GPR A	2.21	0.87	9.69%	42%
Calibrated 1.5 GHz Ground-Coupled GPR	3.56	0.02	19.98%	63%
Calibrated 1 GHz Air-Coupled GPR B	3.75	0.85	13.49%	21%
Calibrated Impact Echo	4.53	0.36	33.08%	100%
Calibrated 800 MHz, 1.2 GHz, 1.6 GHz, and 2.3 GHz Ground-Coupled GPR	4.83	0.77	13.98%	95%
1.5 GHz Ground-Coupled GPR4	4.89	0.01	24.30%	63%
Impact Echo	4.93	0.31	35.65%	100%
Calibrated 1.5 GHz Dual Ground-Coupled CMP GPR	6.08	0.02	15.05%	58%
1.5 GHz Dual Ground-Coupled CMP GPR	6.56	0.04	18.44%	63%
1 GHz Air-Coupled GPR B	7.80	0.16	43.22%	37%
Calibrated 2 GHz Ground-Coupled GPR	10.24	0.12	25.34%	100%
Calibrated 3D GPR	10.62	0.02	28.44%	100%

Device	Average Difference Error ^a (cm)	R ² value ^b	% Error ^c	% Test Locations Measured ^d
800 MHz, 1.2 GHz, 1.6 GHz, and 2.3 GHz Ground-Coupled GPR	10.95	0.09	33.19%	100%
Calibrated 900 MHz and 1.5 GHz Ground-Coupled GPR	11.80	0.00	30.89%	100%
3D GPR	15.05	0.02	38.33%	100%
2 GHz Ground-Coupled GPR	19.10	0.02	52.54%	100%
900 MHz and 1.5 GHz Ground-Coupled GPR	27.22	0.07	83.69%	100%
^a Difference error was calculated as the absolute difference between the device predicted thickness and the actual thickness of the core. These errors for all the test locations were averaged for each method. ^b Coefficient of determination ^c Percent error was calculated by taking the absolute difference between the thickness predicted with the devices and the actual thickness of the core, dividing this difference by the actual thickness, and multiplying by 100. ^d Percentage of test locations measured by the device; some devices were unable to provide estimated thicknesses at some of the locations. ^e An outlier, at test location 33, was removed from this dataset to provide a more accurate representation of the results. The error at this location was significantly different than the others, as can be seen in Figure 3. ^f The MISW was broken during testing so data for the remaining sections were not able to be collected.				

The ultrasonic tomography device was the only one able to measure all the PCC test locations with a low average difference error (1.09 cm) without a calibration process. The R² value was 0.99, and the percent error was 4.28%. It was easy to use, provided real time measurements, and did not require calibration to achieve this accuracy for the PCC test locations. Limitations of the ultrasonic tomography device include the inability to detect more than one layer at a time, because it only detects changes within the pavement. If there is a change in the pavement, i.e., a void, then the shear wave would be reflected back to the surface, and therefore, other changes deeper within the pavement, such as the pavement layer interface, would not be measured. Additionally, only the top pavement layer could be measured with the ultrasonic tomography device, so composite pavements would not be detected, and base and subbase layer thicknesses could not be determined either. It should also be noted that there was intermittent rain throughout the day during testing. However, rain does not affect the data as long as there is no standing water on the pavement to be tested.

The impact echo device had the lowest error once the data was calibrated with core data and an outlier was removed. The impact echo device measured 100% of the test locations. With all of the original data, the impact echo device provided data with an average difference error of 4.93 cm and 4.53 cm when calibrated. However, upon inspection of the data, it was clear that at test location 33, the measurement was significantly different from the remainder of the data (Figure 3). Once this outlier was removed, the average difference error dropped significantly to 1.13 cm and to 0.82 cm when calibrated. For this corrected dataset, the calibrated R² value was 1, and the calibrated percent error was 2.07%. The impact echo device was also easy to use and was able to provide real-time results.

The MISW also provided low error data, with an average difference error of 1.47 cm. When calibrated, the average difference error decreased to 0.86 cm. Only 53% of the PCC test locations were measured. However, this was not because the system was unable to collect the data, but because the equipment was broken during

testing. Therefore it is difficult to draw final conclusions from this data. The MISW was quite time and labor intensive for both data collection and processing. An automated version of this device would be required for implementation.

The calibrated 1 GHz air-coupled GPR A also had a relatively low error of 1.3 cm, but was only able to measure 42% of the PCC test locations. As expected, the GPR signal was attenuated by the PCC pavement material.

Effect of Calibration

All of the devices tested in this study provided calibrated data except for ultrasonic tomography device (Table 3). The calibration process improved the accuracy of all the devices. Generally, the ground-coupled GPR systems improved by a greater margin, because the dielectric constants have to be estimated during initial data collection, and the amount of improvement depends on how close the assumed dielectric constant was to the actual dielectric constant. If the assumed value is close, then the accuracy of the initial results will be good, but there is not a way to verify the assumed value without further investigation, such as coring.

Table 3. Effect of calibration on the error measurements.

Method	Initial Error ^a (cm)	After Calibration Error (cm)	Difference (cm)	% Improvement
900 MHz and 1.5 GHz Ground-Coupled GPR	27.22	11.80	15.42	57%
2 GHz Ground-Coupled GPR	19.10	10.24	8.86	46%
800 MHz, 1.2 GHz, 1.6 GHz, and 2.3 GHz Ground-Coupled GPR	10.95	4.83	6.12	56%
3D GPR	15.05	10.62	4.43	29%
1 GHz Air-Coupled GPR B	7.80	3.75	4.05	52%
1.5 GHz Ground-Coupled GPR	4.89	3.56	1.33	27%
1 GHz Air-Coupled GPR A	2.21	1.30	0.91	41%
MISW	1.47	0.86	0.61	42%
1.5 GHz Dual Ground-Coupled CMP GPR	6.56	6.08	0.48	7%
Impact Echo	4.93	4.53	0.40	8%
Corrected Impact Echo	1.13	0.82	0.31	27%
^a Error was calculated as the absolute difference between the device predicted thickness and the actual thickness of the core. These errors for all the test locations were averaged for each method.				

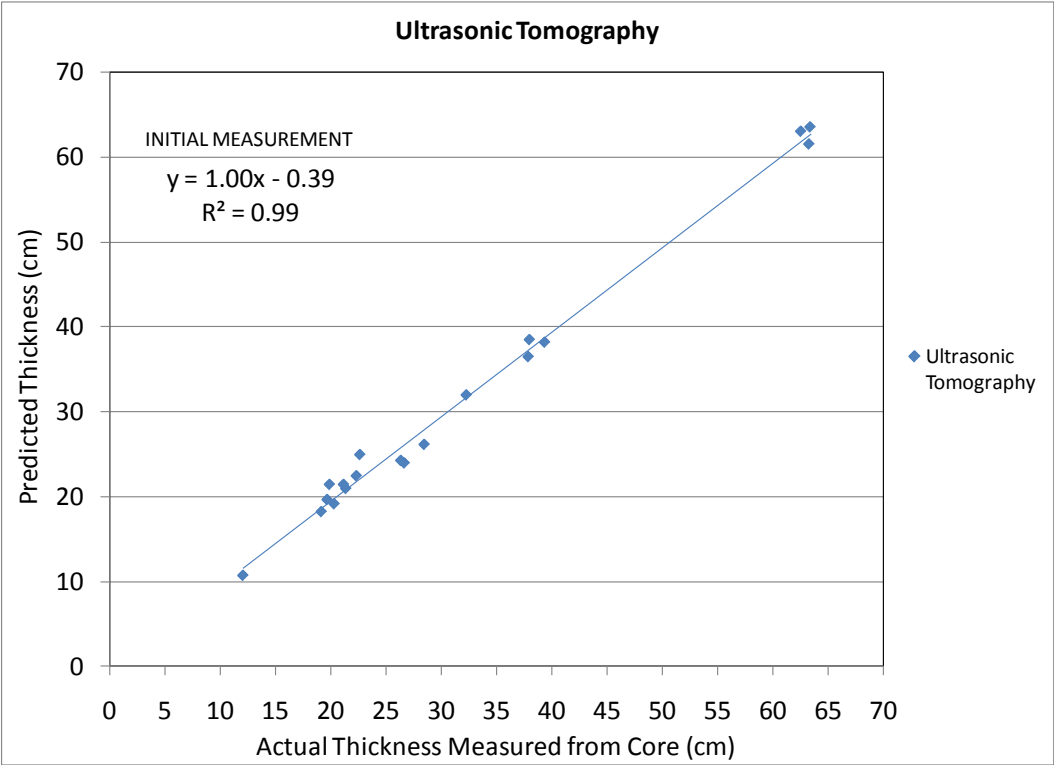


Figure 2. Predicted thicknesses versus actual measured thicknesses for the ultrasonic tomography method.

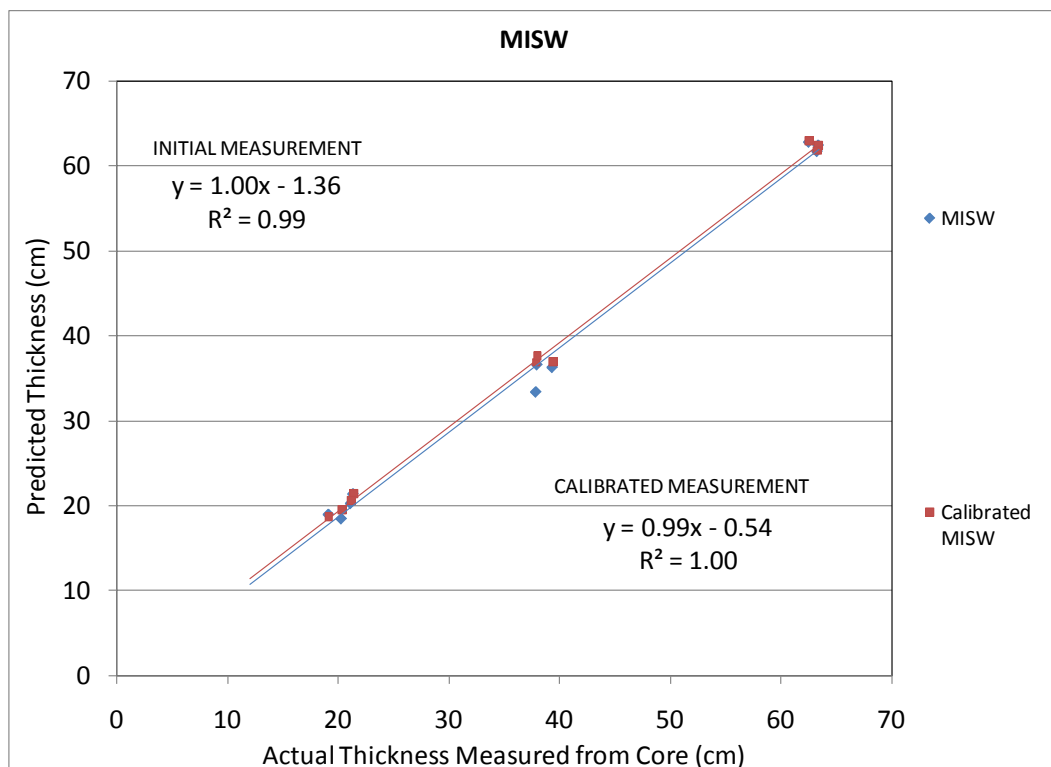
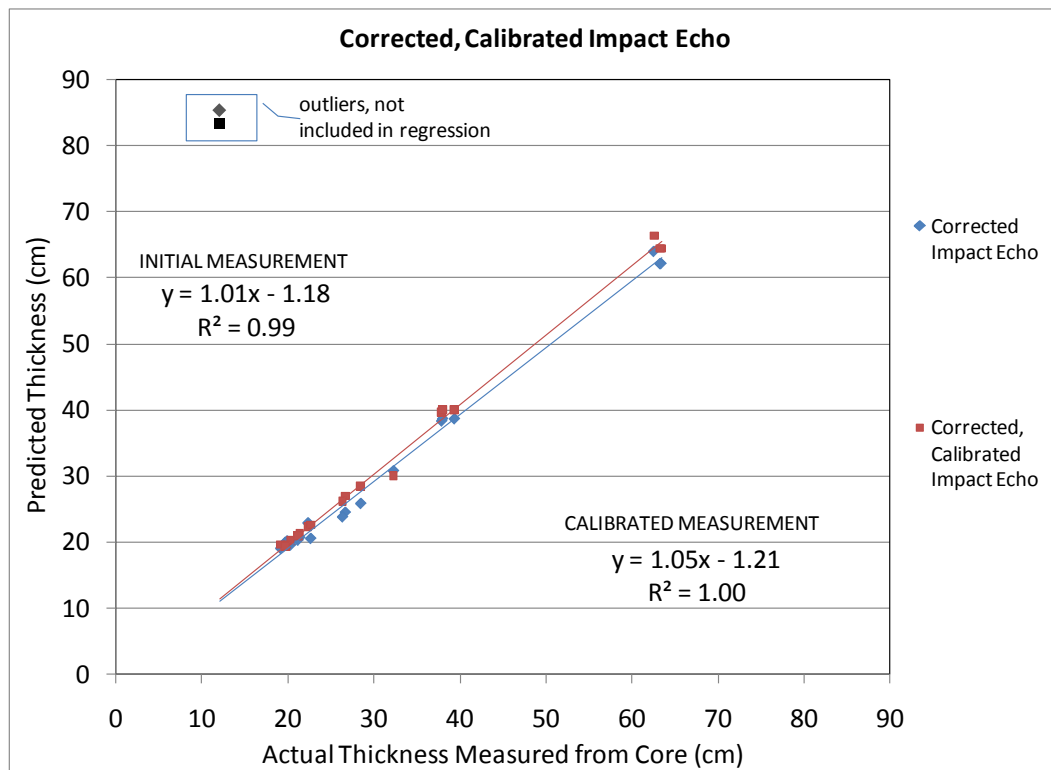


Figure 3. Predicted thicknesses versus actual measured thicknesses for the seismic devices, including impact echo and MISW.

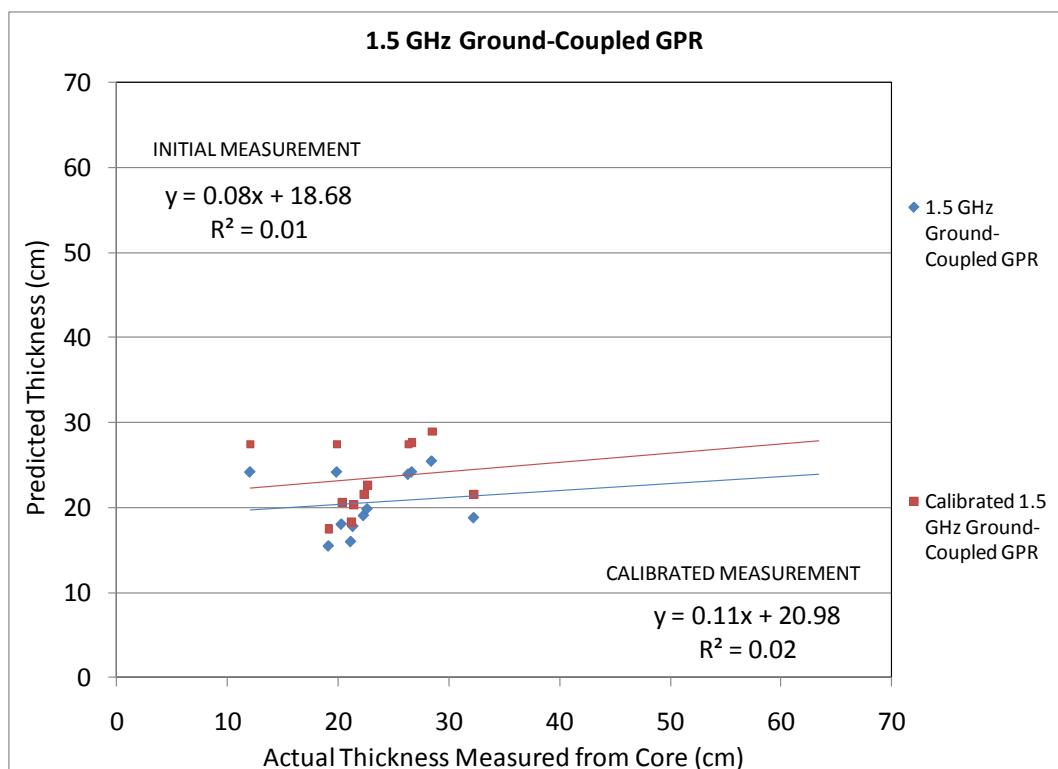
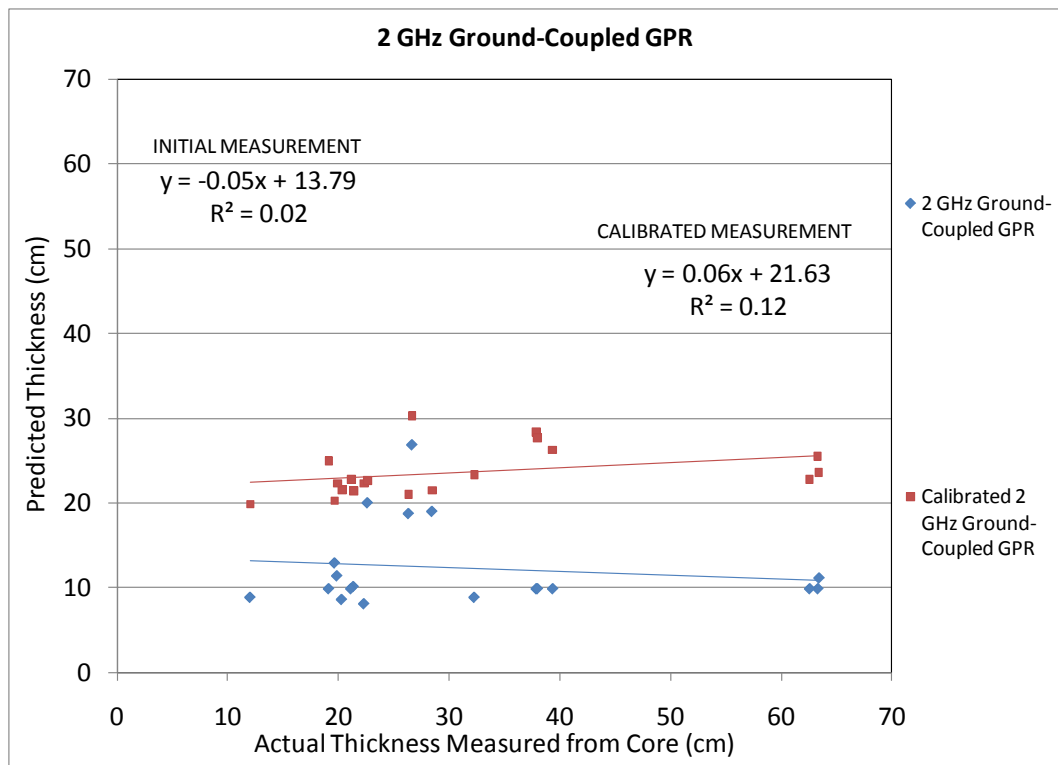


Figure 4. Predicted thicknesses versus actual measured thicknesses for the single antenna ground-coupled GPR devices (2 GHz and 1.5 GHz).

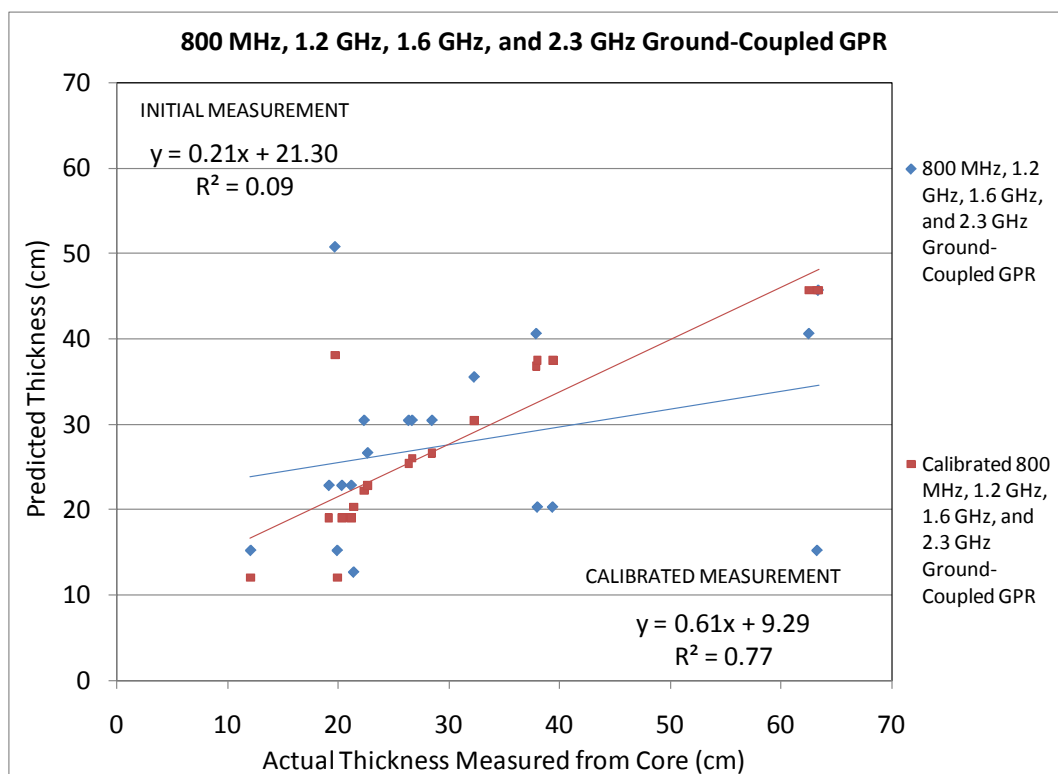
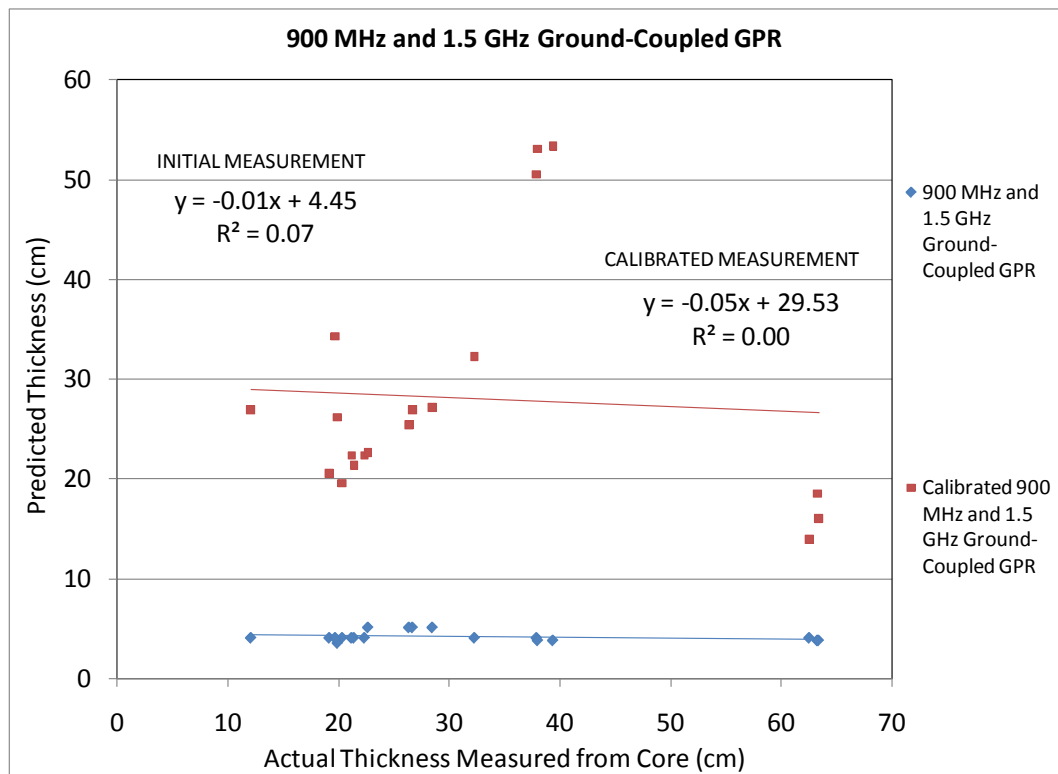


Figure 5. Predicted thicknesses versus actual measured thicknesses for the multi-antenna ground-coupled GPR devices.

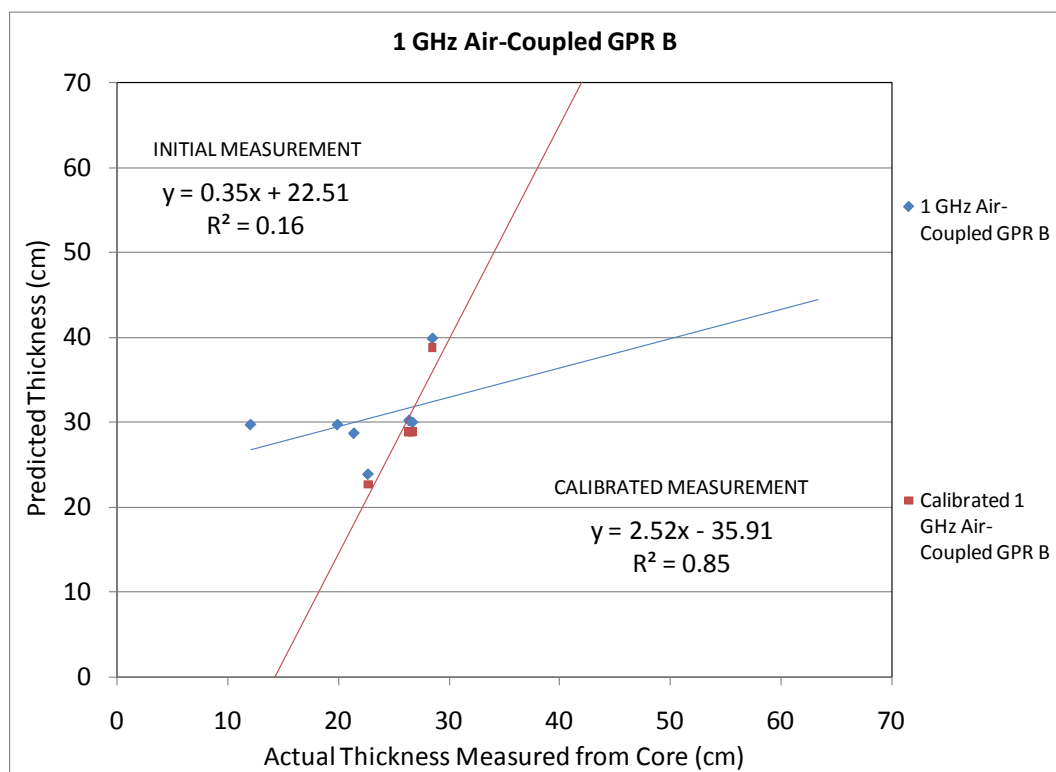
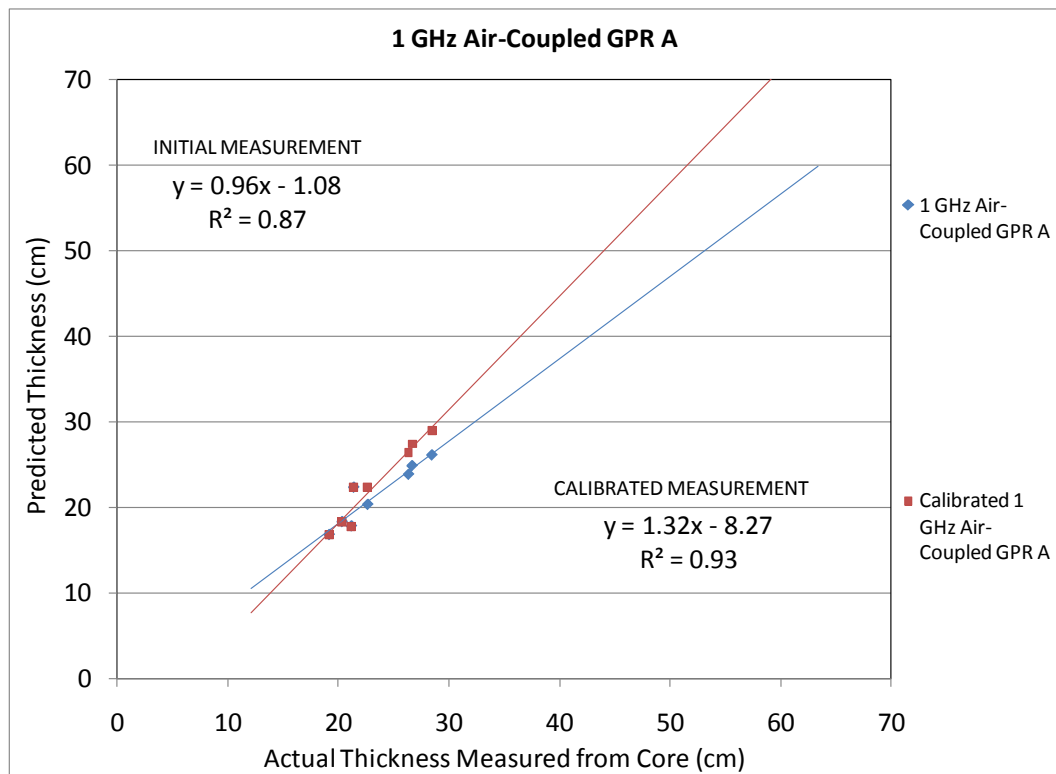


Figure 6. Predicted thicknesses versus actual measured thicknesses for the single antenna air-coupled 1 GHz GPR devices.

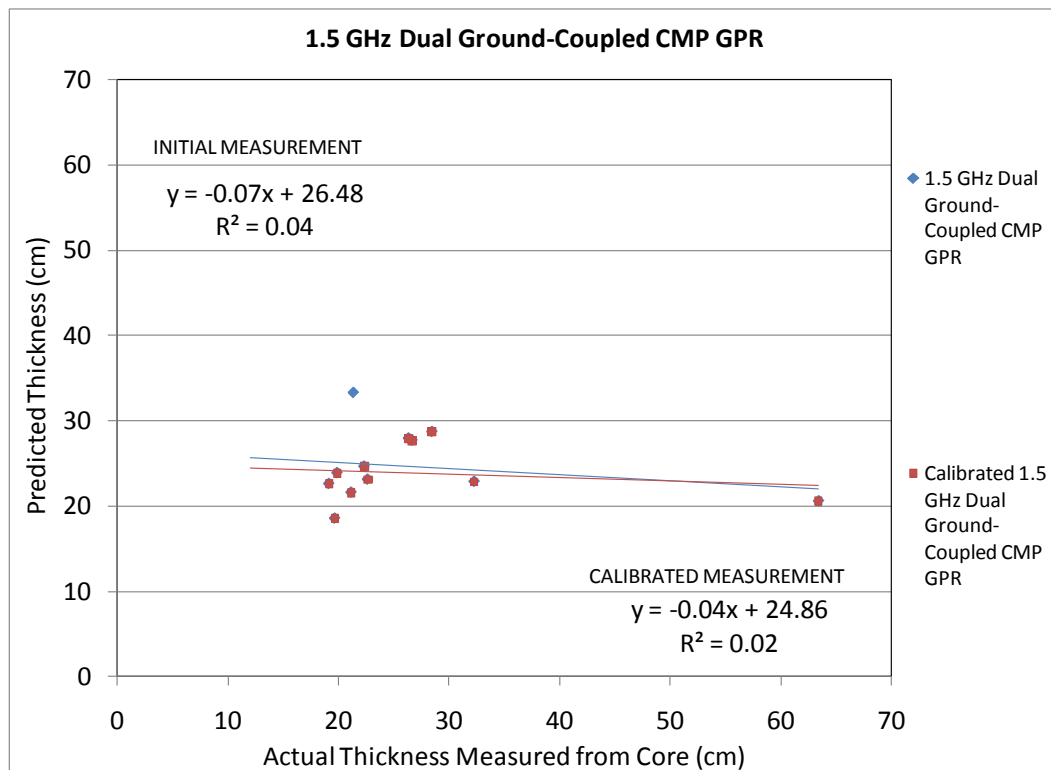


Figure 7. Predicted thicknesses versus actual measured thicknesses for the 1.5 GHz dual antenna ground-coupled GPR device.

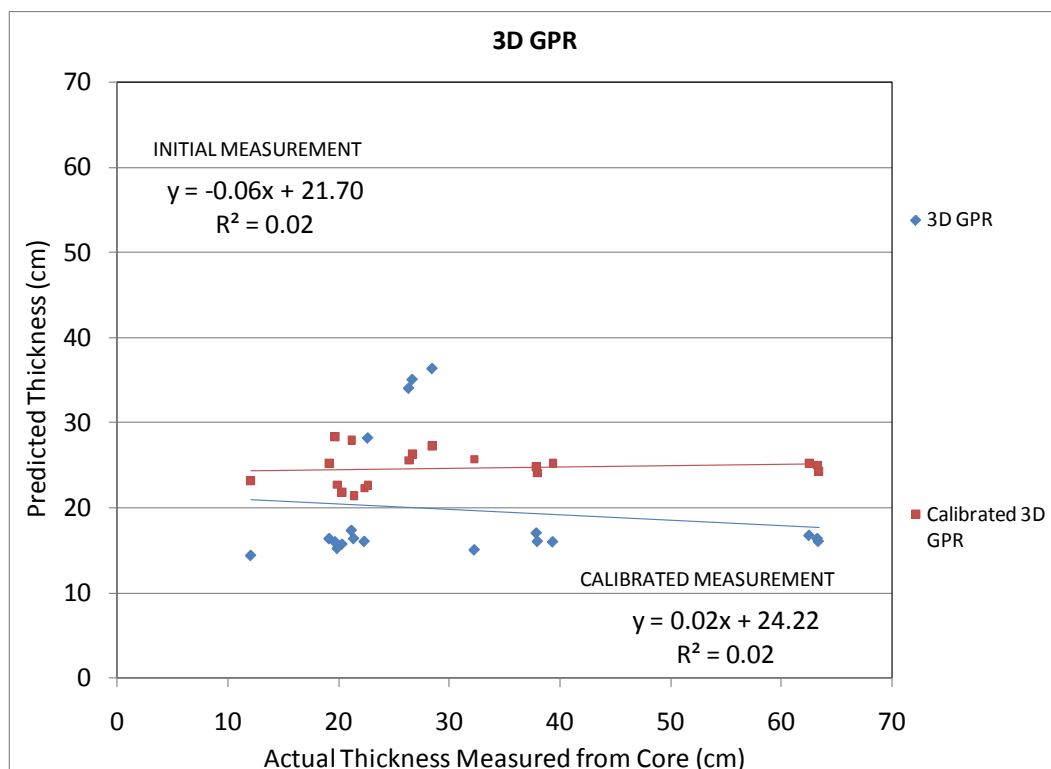


Figure 8. Predicted thicknesses versus actual measured thicknesses for the 3D GPR device.

Conclusions

The ERDC performed field evaluations of nondestructive testing devices to measure pavement thickness. The main measure of error, defined as the absolute difference

between the device-measured thickness and actual core thickness, was used to gauge the performance of the devices. The coefficient of determination and percent error were also computed for a more descriptive evaluation of the devices.

The ultrasonic tomography device performed the best overall, because it had a low error (1.09 cm), did not need calibration to achieve this accuracy, and was able to measure 100% of the test locations. Additionally, the MISW, impact echo, and 1 GHz air-coupled GPR A all performed well with average difference errors less than 1.5 cm, R^2 values greater than 0.9, and percent errors less than 7%. The MISW and impact echo had results that fell into this range without calibration, but the 1GHz air-coupled GPR A required calibration to reach this criteria.

Calibration by taking cores and recalculating the thickness data improved the performance of the devices. Coring in one location per pavement type is recommended for all devices for optimal accuracy. Ground-coupled antennas required calibration cores to improve the accuracy, because their accuracy depended on how close the estimated dielectric constant was to the actual pavement dielectric constant. Determining which ground-coupled frequency to use is difficult because penetration depends on the material. Two devices, the ultrasonic tomography device and the impact echo device, were able to provide feasible thicknesses with average errors less than 1.25 cm without the need for calibration. This is beneficial for military missions when calibration may not be feasible.

Ease of use is extremely important for the implementation of these devices. The ultrasonic tomography device would require the least amount of training and experience. Simply following step-by-step instructions would result in thickness measurements. The impact echo device was also simple to use. However, for thick pavements, the built-in impactor is not sufficient and the hammer would be required. Experience with the device would be required for accurate and consistent results. The GPR methods, both horn antennas and ground-coupled antennas, would require a trained user with experience, especially if the layer interfaces are difficult to detect. The MISW was extremely time intensive and would require a trained user to post-process the data.

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