

DEVELOPMENT OF GROUND PENETRATING RADAR CURRICULUM FOR LOCAL
GEORGIA AGENCIES

by

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(Under the Direction of Stephan A. Durham)

ABSTRACT

The number of employees and the general budget are limited for many municipal governments. As a result, it is necessary to have reliable tools for asset management. Failure to properly manage infrastructure damages personal property and public infrastructure. Often times, warning signs are only detectable using invasive evaluation methods. One of the most applicable yet intimidating tools for noninvasive evaluation is Ground Penetrating Radar (GPR). This research uses a literature review to evaluate GPR, its applications, and existing educational materials for GPR operators. A statewide survey of Georgia agencies revealed significant interest in GPR and the challenges associated with the technology. A curriculum based on the experiences and needs of agencies was created to educate Georgia municipalities on how to access GPR. Case studies evaluated the curriculum's feasibility, functionality, and success. Ultimately, this work is to further the implementation of GPR by local governments regardless of their size and resources.

INDEX WORDS: Ground Penetrating Radar (GPR), American Public Works Association (APWA)

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1.0 | INTRODUCTION

The number of employees and the general budget are limited in municipal governments. As a result, it is important to have reliable and efficient resources at their disposal to assist with asset management. Failure to properly manage infrastructure can lead to damage to personal property and public infrastructure with some such failures only detectable using invasive evaluation methods. One of the most widely applicable yet intimidating tools for asset evaluation is Ground Penetrating Radar (GPR). GPR is a non-destructive testing method that can evaluate structures, locate utilities, and perform geotechnical investigations.

This research uses a literature review to evaluate GPR, its many applications, and the existing education and training materials for GPR operators. A survey of Georgia local governments revealed significant interest in using or improving their use of GPR and the challenges associated with doing so. A curriculum based on the experiences of other agencies was created following the review and survey analysis to educate interested Georgia municipalities on how to implement GPR in their work. Case studies will evaluate the feasibility and success of the curriculum and provide a review of its functionality and needs for improvement. Ultimately, this work is made to further the implementation of GPR by local governments regardless of their size and scale of resources.

1.1 | Structure of Thesis Chapters

This thesis is organized into seven distinct chapters with Chapter 1 as the introduction. Chapter 2 presents the motivating factors for the development of a GPR guide and curriculum. This chapter includes a preview of what municipalities have to gain from the use of GPR and the history of

GPR research at the University of Georgia. Chapter 3 details the technology behind GPR, its history, development, and applications, as well as a review of the existing GPR education and training available to municipalities. Chapter 4 contains the problem statement, including the research objectives and significance. Chapter 5 explains the research methodology and the stages of data collection, analysis, and curriculum development. Chapter 6 provides an analysis of the research findings and justifications behind the choices made concerning the curriculum content. Chapter 7, the final chapter, includes the conclusions and recommendations for future work determined throughout the first six chapters.

2.0 | BACKGROUND

2.1 | GPR for Asset Management

The many applications of GPR, discussed in section 3.3, make it widely applicable to the services provided by local Georgia governments. In addition to saving time, money, and effort compared to traditional methods, GPR produces continuous profiles of the subsurface subject rather than localized samples such as pavement cores. This method is significant in asset management because it can identify points of potential failure across a great distance before warning signs become present at the surface. The ability to identify signs of distress allows municipalities to better plan their budget for construction needs and save money by eliminating the cost of potential damage to items like private property and utility lines.

2.2 | Public Interest

In a 2021 article from the U.S. Department of Transportation's Public Roads Magazine titled "How 10 States Use, Evaluate, and Implement Nondestructive Evaluation [NDE] Technology", ten states provided feedback concerning their use of NDE technology like GPR (Azari, 2021). One of the questions asked was: How Can FHWA Help? The most common response to this question was a request for support regarding training methods and resources for evaluating the potential usefulness of certain technologies from an unbiased source other than equipment manufacturers. In addition, there was a common suggestion to implement a platform for DOTs to use for knowledge sharing, advice, and techniques for NDE use. The FHWA's strategic plan outlined in Figure 1 and strategy 3.5 is to "assist in developing training curricula, standards, and certification related to assessment technology." This goal of theirs establishes that there is a need for more

publicly funded and created resources on GPR operation and that there is potential that a resource, like what this research is developing, will help to shape the future work in this area.

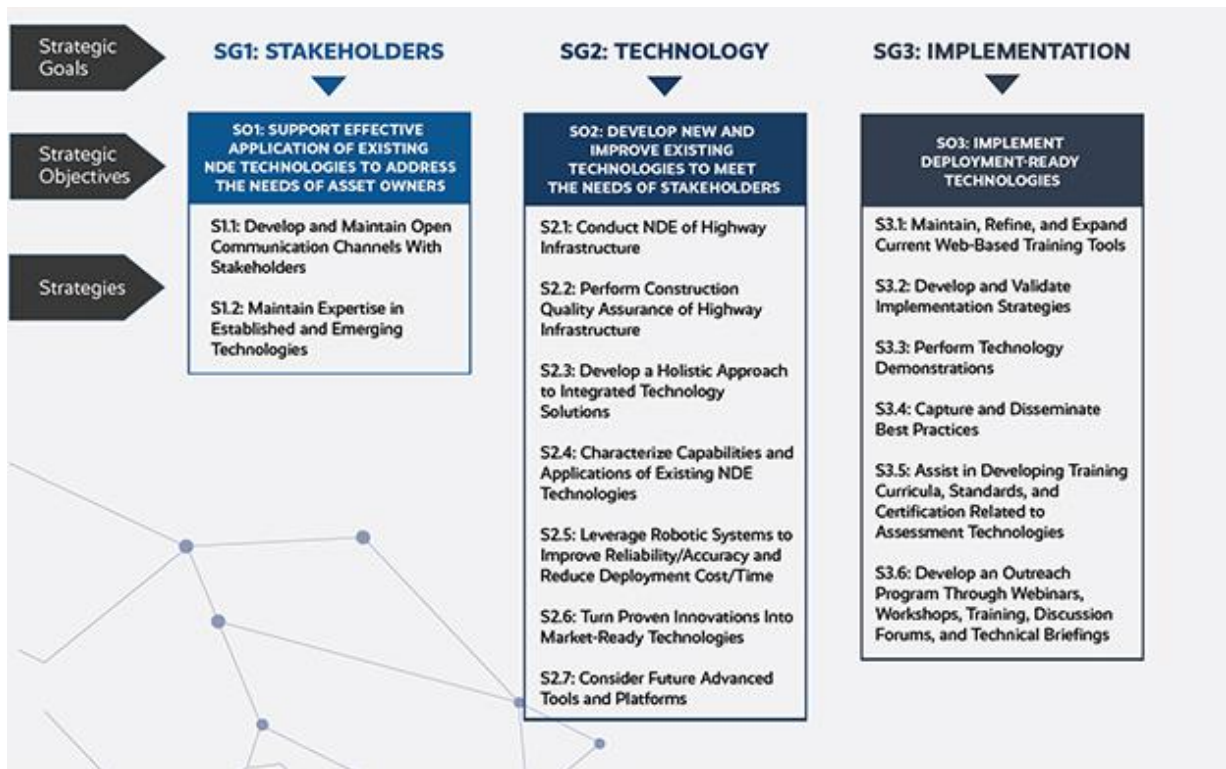


Figure 1: The strategic plan for FHWA’s NDE Program (Azari, 2021)

2.3 | GPR Research at the University of Georgia College of Engineering

The University of Georgia College of Engineering, under the leadership of S. Sonny Kim, has conducted GPR research studies on pavement performance and soil properties testing. A 2017 project by Johnson et al. studied the practice of forensic investigation techniques applied to rigid and flexible pavements in North America. The study determined that the two most effective and commonly used nondestructive evaluation (NDE) techniques are falling weight deflectometers and ground penetrating radar (GPR). Following this, a pilot investigation was conducted to determine the effectiveness of the pavement investigation procedure recommended by the National Cooperative Highway Research Program (NCHRP) on jointed plain concrete pavement (JPCP).

The pilot investigation findings were consistent with the initial study findings and determined that these techniques are effective for JCPC evaluations.

A 2018 study by Durham et al. evaluated the performance of Georgia's CRCPs using GPR compared to pavement core sampling. The study confirmed that GPR is a reliable tool and that the location and depth of reinforcement affect the potential for cluster cracking and punchouts.

Following Johnson et al., a 2018 study by Chorzepa et al. was performed with the Georgia Department of Transportation (GDOT) to evaluate and review the guidance from the NCHRP on forensic pavement evaluation using both nondestructive and destructive tests to investigate continuously reinforced concrete pavement (CRCP) performance. The review was ultimately used to determine the guidance's compatibility with current Georgia practices. Investigating two CRCP sections exhibiting closely spaced cluster cracks determined that the cluster-cracking mechanism was related to material and environmental factors. The punchouts in the section in poor condition were due to construction issues like poor concrete compaction. This study was used to develop and recommend a long-term monitoring program to identify signs of punchout stress and provide opportunities for pavement rehabilitation. A second study by Chorzepa et al. was performed in 2019 to evaluate the same concerns in jointed plain concrete pavements (JPCP).

Citir et al. 2020 used GPR to investigate the factors affecting CRCP distress. This study was performed to understand why certain sections of CRCP perform well while others have significant structural distress. The research confirmed the correlation between signs of distress like cluster cracking and punchouts and the location and depth of reinforcement.

Additional GPR research, specifically for both pavement and geotechnical engineering includes the following. A 2020 study by Abdelmawla & Kim presents a method to estimate the density and water content of subgrade soils using GPR data and a simple exponential model. The

results of the model show that using NDT methods to estimate subgrade soil density can efficiently anticipate pavement deterioration and potential risks to the subsurface pavement structure. A following study in 2020 by Tihey & Kim researched using GPR to estimate the resilient modulus of fine-grained soils. This study was performed to determine if the repeated load triaxial test method can be replaced by GPR to rapidly calculate the resilient modulus of soil for design. Abdelmawla & Kim expanded on their 2020 work with a 2021 study on how to predict the subgrade soil density using GPR and the dielectric constants of soils. The study developed a mathematical model to use electromagnetic mixing formulae and dielectric constants to predict the dry density of subgrade soils. In 2021 Kim et al. studied how to improve pavement maintenance and rehabilitation strategies using GPR technology to assess and monitor pavement conditions. The goal of this research is to improve how pavements are monitored to make maintenance and rehabilitation a more cost-effective process.

3.0 | LITERATURE REVIEW

3.1 | Ground Penetrating Radar

GPR is a non-invasive surveying technique that uses electromagnetic pulses to detect structural and material features of subsurface composite areas (Annan, 2002). Scanned areas are typically below ground or within fabricated objects (Penhall, 2022). GPR's most common use is as a non-destructive geophysical observation tool to find buried objects and obscured geologic features (Guo et al., 2013). The increase in the use of GPR is directly related to the development of its various applications over time. Throughout its history, GPR's unique ability to detect any change in material properties means that it can simultaneously survey plastic, metal, fabricated, and natural surfaces (Annan, 2003). As a result, the technology has been implemented as an archaeological tool to efficiently locate buried artifacts, a method to measure the depth of ice in glaciers and the distance to underground water tables, and even to study the properties of the moon's crust (Conyers, 1998). Current applications of GPR in civil engineering include preventative asset monitoring, geotechnical and structural inspections, utility line and vault locating, and informing design choices (Benedetto & Pajewski, 2015).

3.1.1 | Principles of Ground Penetrating Radar

A GPR system typically consists of five main components including a control unit, an antenna, an internal or external power supply, a data storage and monitoring device, and a distance measurement device. Depending on the system, the data storage and monitoring device is a part of the control unit, like the system in Figure 2, or it is a separate device.



Figure 2: GPR Equipment Diagram (GSSI, 2018)

More advanced units process the data in the moment and produce images as the ground is surveyed, but many still store the raw data and export it to be processed elsewhere. Live processing or not, the raw data points must be saved so that further analyses are not limited to observing the two-dimensional image (Utsi, 2017).

As demonstrated in Figure 3, the control unit works by initiating an electromagnetic pulse through the transmitter antenna into the ground surface. As the pulse travels through the ground, parts of the signal reflect to the receiver antenna each time the conductivity and dielectric constant of the subsurface material change. This change occurs as the electromagnetic wave crosses from one material into another. These reflections produce a layered one-dimensional view of the subsurface. GPR can form a two-dimensional image by sending out multiple pulses in a row while moving across a distance and then stacking the one-dimensional views to create a profile shown in Figure 4 (Bigman, 2018; GSSI, 2018; Utsi, 2017).

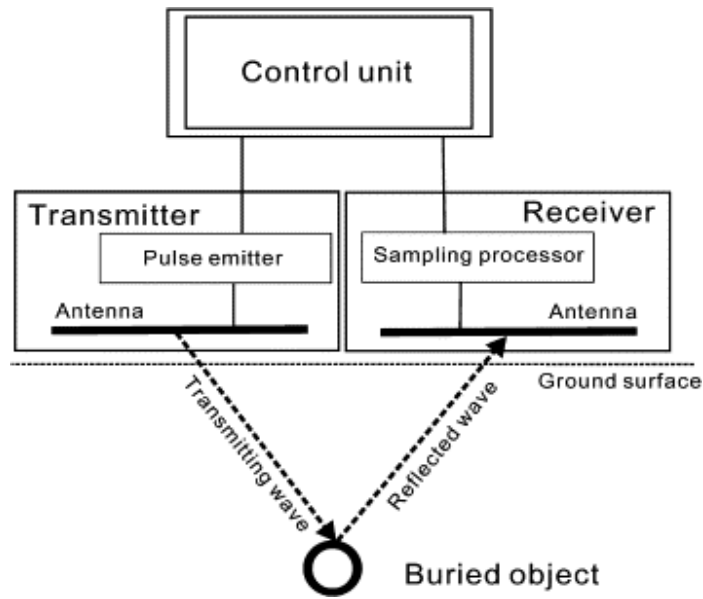


Figure 3: Block Diagram of a GPR Electromagnetic Pulse (Xu et al., 2010)

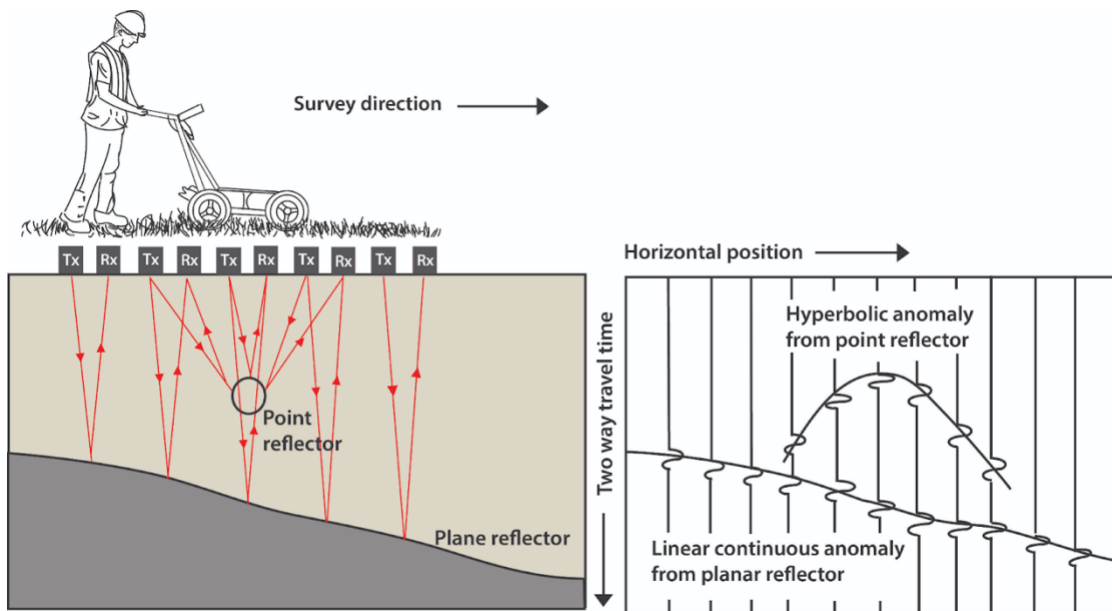


Figure 4: GPR imaging method (ScanTech Geoscience, 2021)

The receiving antenna is a certain measurable distance from the transmitter. The space between the two causes the radar energy to travel along a triangular path instead of straight, which creates a range of energy shaped like the cone in Figure 5.

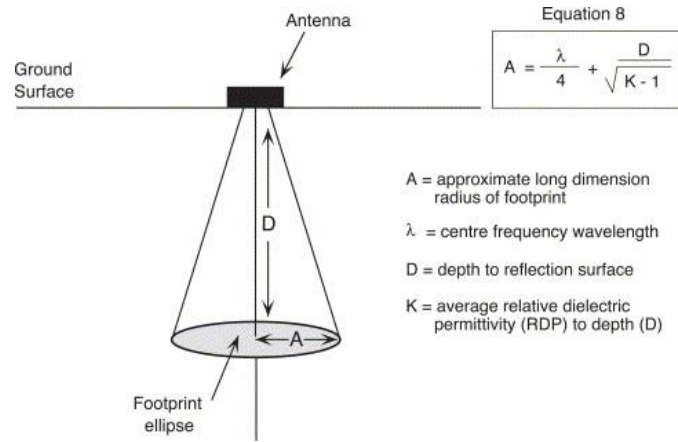


Figure 5: Calculating the footprint of the cone-shape of energy emitted from a GPR antenna (Conyers & Goodman, 1997; Annan, 2002; Neal, 2004)

The cone of energy is what creates the profile’s hyperbolic shape. When the edge of the cone first reflects off the object, the travel time from the transmitter is longer than the travel time back to the receiver. Though the depth measurement at this point is greater than the actual depth, it establishes the first point of the parabola. As the unit moves over the object, the travel times to and from the antennas get closer until they are equal at the object’s shallowest point, which becomes the vertex of the parabola. As the unit moves away, the parabola decreases until it ends when the different material is no longer within the cone’s range (GSSI, 2018; Ristic et al., 2017; Xie et al., 2021). Figure 6 shows the process of generating a hyperbolic reflection.

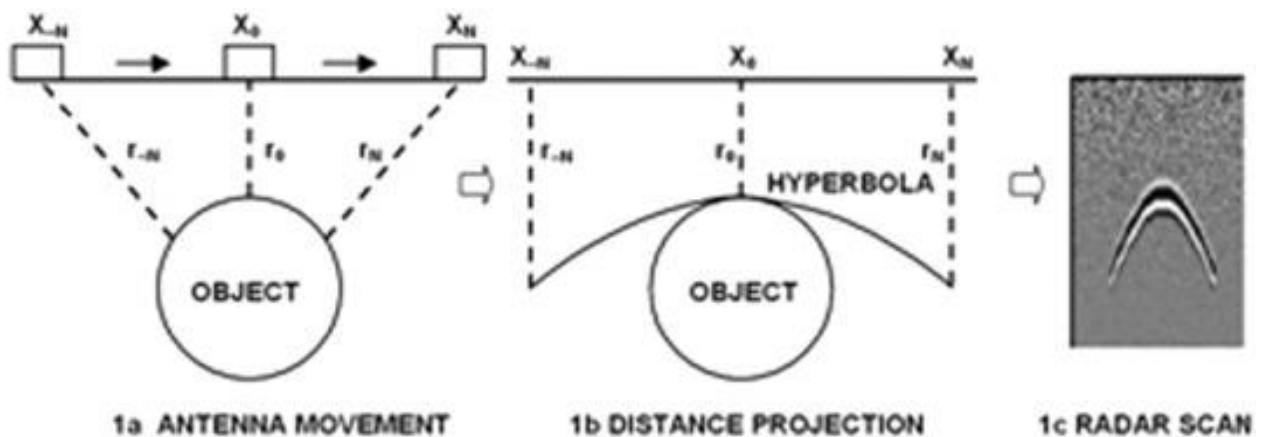


Figure 6: Steps to generating a hyperbolic reflection (Ristic et al., 2009)

GPR has the advantage over other geophysical mapping methods as it can collect, measure, and model data in three dimensions, shown in Figure 7 (Bigman, 2018). Bigman explains how data can be imaged as cake layers whereby viewing the scan in the third dimension would be like looking at each layer from above. These layers are known as time slices. Then, if one were to cut a slice and look at it from the side, the layers separated by frosting would represent the two-dimensional vertical profile, like the parabola image in Figure 6. Time slice views allows surveyors to track the horizontal path of objects like pipes and utilities and differentiate between closely spaced parallel objects.

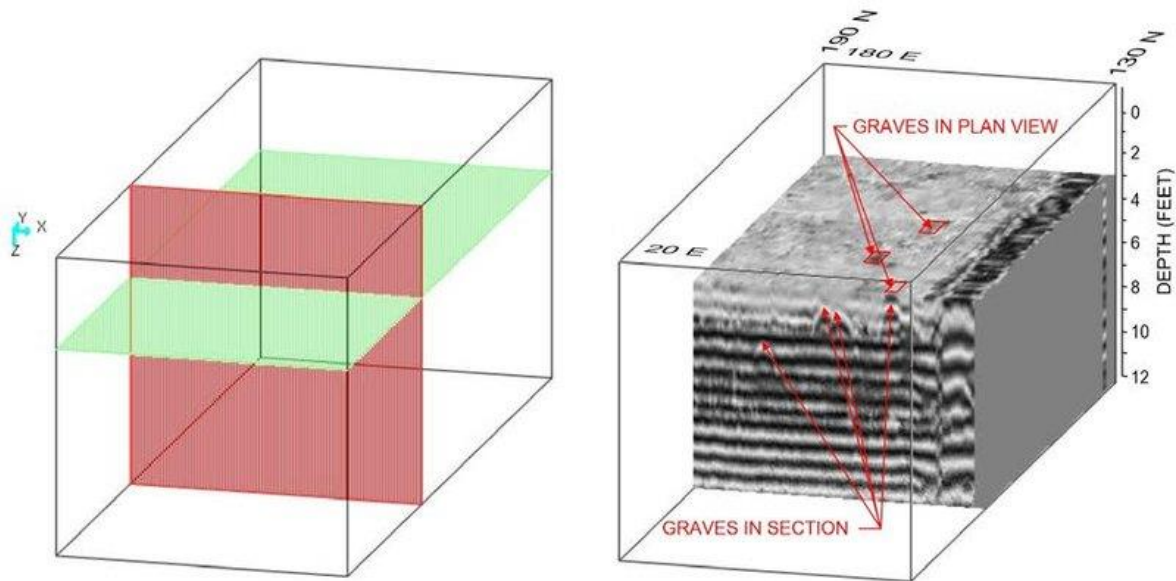


Figure 7: Example 3D block from Beechwood Cemetery. The green horizontal rectangle represents a time slice, and the red vertical rectangle, a 2D vertical profile. (Johnson et al., 2015)

3.1.2 | Influential Factors

The accuracy of a GPR survey depends on the properties of the material it travels through, the existence of buried or obscured surfaces, and the frequency of the antenna(s) used. If the proper steps are not taken to consider the technical details of the survey, the results will be unreliable or

unusable. Attempting to image a surface saturated with water may lead to complete signal attenuation and choosing the wrong antenna frequency may lead to the survey being unable to reach, or obscuring, subsurface obstacles.

3.1.2.1 | Material Properties

A material's electromagnetic properties change the velocity of the antenna's wavelength, which influences the accuracy of a GPR survey or even cause the scan to be inconclusive (Utsi, 2017). The three physical material properties that affect the performance of GPR are dielectric permittivity, electrical conductivity, and magnetic permeability. These properties are a measure of the soil and rock matter, water content, and bulk density of the material (ASTM, 2020; Bigman, 2018). The most important factors are the material's dielectric permittivity and electrical conductivity (Benedetto & Pajewski, 2015). The relative dielectric permittivity (RDP) influences the average velocity of the wavelength and the lower the RDP, the more ideal the material is for GPR. Table 1 is a combination of common materials and their approximate RDP, conductivity, and velocity. The material with the lowest RDP and highest average velocity is air and aside from metal which has a near-infinite RDP, water is the material with the highest RDP and lowest average velocity. The RDPs of metals are not factored into decision-making because metals are complete reflectors and do not allow any amount of GPR energy to pass through them. Unless the wavelength is small enough to pass through gaps between the pieces of metal, anything below metal sheets, fine metal mesh, or pan decking will not be visible to a GPR survey (Bigman, 2018; Utsi, 2017).

Table 1: The approximate RDP, conductivity, and velocity of commonly surveyed materials (Maruddani & Sandi, 2019)

Material	Relative Permittivity	Conductivity (mS/m)	Average Velocity (m/ns)
Air	1	0	0.3
Ice	3-4	0.01	0.16
Anhydrites	3-4	0.01-1	0.13
Dry Sand	3-5	0.01	0.15
Granite	4-6	0.01-1	0.13
Limestone	4-8	0.5-2	0.12
Shale	5-15	1-100	0.09
Silts	5-30	1-100	0.07
Saturated Sand	20-30	0.1-1	0.06
Clays	5-40	2-1000	0.06
Freshwater	80-81	0.5	0.033
Seawater	80-81	3000	0.01

Materials with high conductivity are challenging to survey with GPR because the rate of signal attenuation increases as conductivity increases. Attenuation is the reduction in signal strength over time. It is accelerated by conductivity because as the GPR wave travels through the material it will collide with the free electric charges present, which creates friction, causing the signal to lose energy in the form of heat. Since water has a higher conductivity than air, materials can be quickly identified as conductive if saturated. Because of this, a site could have different conductivity values based on how recent the last rainfall event occurred and if it was high or low tide in coastal regions. When designing a survey, the area should be thoroughly checked for signs of water penetration due to rain or pipe leaks, and concrete should not be surveyed until it has hardened. Materials with high silt and sand contents will be less conductive than those with salt

and clay, which causes the signal to decay rapidly. Due to its components, saltwater causes signals to attenuate almost instantly (Bigman, 2018; GSSI, 2018; USDA, 2014).

The functionality of a GPR survey depends on the relationship between the material's dielectric constant and electrical conductivity. A GPR signal will reach greater depths if the signal can travel quickly while losing minimal strength. This combination occurs in materials with a low RDP and low conductivity including dry sand and granite bedrock. Materials with this relationship between RDP and conductivity are typically the most ideal types to survey. Materials like freshwater, with a high RDP and low conductivity, create slow-moving waves that attenuate very little over time. This rate allows for GPR to be used to map lake beds and underground water tables. However, saltwater is highly conductive with a high RDP, so waves traveling through it move slowly and lose strength almost instantly. Highly conductive materials with low RDPs are uncommon. However, they include gasoline, where the signal decays rapidly though the waves still travel at a high velocity until then. Additionally, concrete has a low RDP but is moderately conductive depending on its water content and curing stage. Though these properties can make it difficult to model the physical elements of a site's subsurface, they do not mean that the "less ideal" materials cannot provide adequate detail and information given proper preparation and thought (Bigman, 2018).

3.1.2.2 | Antenna Frequency

Selecting the ideal antenna frequency for a survey depends upon two features, the preferred survey penetration depth and resolution. The penetration depth is the depth to which the signal can collect data, and the resolution depth is the depth to which the signal can identify and differentiate between two closely spaced objects (Sensoft, 2016). A higher frequency creates shorter wavelengths, which are absorbed faster than a lower frequency wavelength. The shorter transmission time of the high-

frequency wavelength creates a more detailed image than a low-frequency antenna but only reaches a shallow depth. As the antenna frequency decreases, the penetration depth increases, but the quality and detail of the image decrease (Abouhamad, 2016; Bigman, 2018). Because of this, when selecting an antenna, the highest frequency still capable of reaching the necessary depth should be used. Refer to Table 2 for a reference of antenna frequencies and their appropriate applications, travel time, and approximate depth range.

Table 2: Antenna frequencies and their applications, travel time, and approximate depth range (Modified from GSSI, 2018; Stryk et al., 2015)

Antenna Frequency (MHz)	Appropriate Application(s)	Travel Time (ns)	Approximate Depth Range
2600	Thickness and condition assessment at shallow depths for structural concrete, roadways, bridge decks, etc.	8-15	0-1.0 ft (0-0.3 m)
1600		10-15	0-1.5 ft (0-0.45 m)
1000		-	0-2.0 ft (0-0.6 m)
900	Archaeology, and the evaluation of the subbase and layer condition of concrete, shallow soil, etc.	10-25	0-3 ft (0-1 m)
400	Archaeology, Shallow geology, and Locating utilities, voids, and storage tanks	20-100	0-12 ft (0-4 m)
270	Geology, Environmental, Utility, Archaeology	50-200	0-18 ft (0-5.5 m)
200	Geology, Environmental, Utility, Archaeology	-	0-9 m (0-30ft)
100	Geologic Proofing	-	0-90 ft (0-30 m)
MLF (16-80 MHz)	Geologic Proofing	-	> 90 ft (30 m)

It is important when selecting the antenna for a project that the size of the wavelength is smaller than the object(s) being measured. If surveying an area with unknown contents, multiple scans using different antennas should be done so that objects too small to be detected by a low-

frequency antenna are not missed and vice versa. Bigman suggests that the wavelength for any antenna frequency and the RDP of the material it is traveling through can be calculated using Equation 1.

$$\lambda = \frac{c}{\nu} \quad (1)$$

Where λ is the wavelength, c is the velocity of the material in meters per nanosecond based on its RDP, and ν is the frequency of the antenna in Gigahertz. Table 3 offers a quick method of estimating the best frequency range to use based on the effect of the material's RDP on the size of the wavelength in meters.

Table 3: Estimated wavelength size in meters for various frequencies and RDPs (Bigman, 2018)

	100 (MHz)	200	300	400	500	600	700	800	900	1000
1 (RDP)	3.00 (m)	1.50	1.00	0.75	0.60	0.50	0.43	0.38	0.33	0.30
2	2.00	1.00	0.67	0.50	0.40	0.33	0.29	0.25	0.22	0.20
4	1.50	0.75	0.50	0.38	0.30	0.25	0.21	0.19	0.17	0.15
6	1.22	0.61	0.41	0.31	0.24	0.20	0.17	0.15	0.14	0.12
9	1.00	0.50	0.33	0.25	0.20	0.17	0.14	0.13	0.11	0.10
10	0.95	0.48	0.32	0.24	0.19	0.16	0.14	0.12	0.11	0.10
15	0.77	0.39	0.26	0.19	0.15	0.13	0.11	0.10	0.09	0.08
30	0.55	0.28	0.18	0.14	0.11	0.09	0.08	0.07	0.06	0.06
40	0.50	0.25	0.17	0.13	0.10	0.08	0.07	0.06	0.06	0.05
75	0.35	0.18	0.12	0.09	0.07	0.06	0.05	0.04	0.04	0.04
81	0.33	0.17	0.11	0.08	0.07	0.06	0.05	0.04	0.04	0.03

Though high-frequency antennas are the best for depicting shallow areas such as structural concrete, bridge decks, pavements, or other objects close to the surface, their short penetration depth limits the applicability of the scans. For example, it might be necessary to know the depth of a crack and if it originated in the pavement subbase or further down in the soil to diagnose the reason behind repeat damage along a section of pavement. Dual-frequency antennas were

developed for areas like this such that the survey could provide a coarse scan of the desired depth and a fine scan of the shallow area (Bigman, 2018). Scanning the same section twice with two individual antennas can produce a similar result. Figure 8 is an image of two scans taken simultaneously by a 250 MHz and 700 MHz dual-frequency antenna. The coarse image produced by the 250 MHz channel reaches a depth of 6.00 m (19.69 ft), and the fine image produced by the 700 MHz channel reaches a depth of 2.00 m (6.56 ft) (Geotools, 2021).

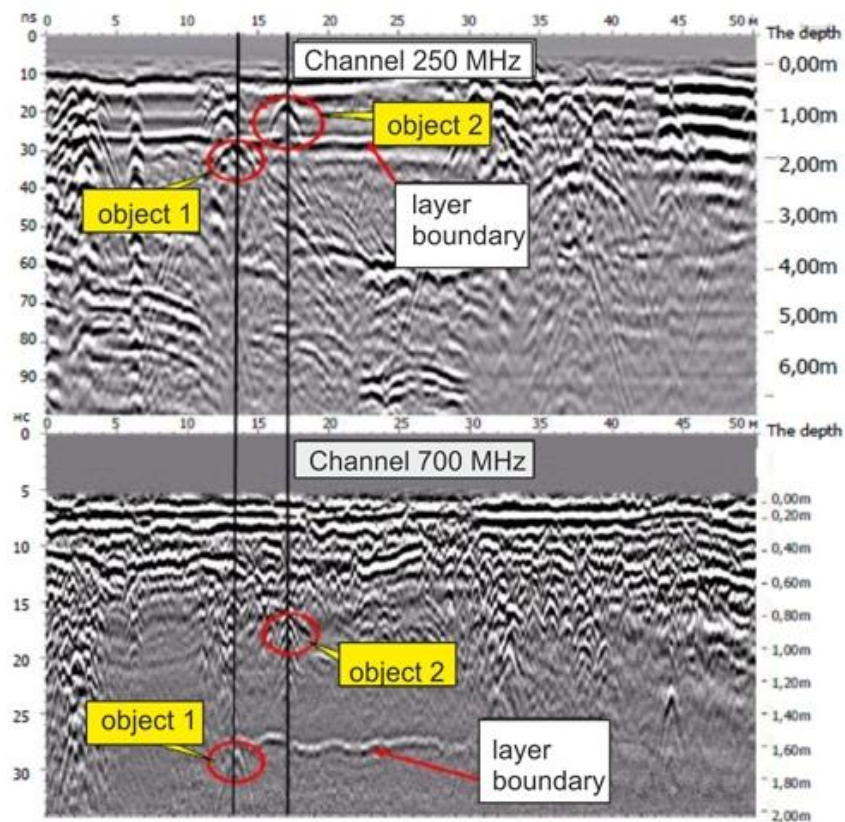


Figure 8: Scan performed by a 250 MHz and 700 MHz dual-frequency antenna (Geotools, 2021)

3.1.2 | Data Processing

After collection, data processing is necessary to refine the calculations and imaging of a surveyed area. Provided that the proper antenna frequency is used and the material properties are agreeable, data processing should improve the GPR signal and allow for more accurate data interpretation. No matter the experience of the operator or choice of equipment, the most influential factors

controlling the quality of processed data are how well the raw data was collected and the type of software applied. The ideal software to use with a unit is typically chosen by the GPR manufacturer and may be internally or externally sourced (Economou et al., 2015). Commercial options available through manufacturers and third parties include GSSI’s RADAN, Sensors and Software’s EkkoMapper, and Dean Goodman’s GPR-SLICE (Wadsworth, 2022). Open-source software options include Python-based GPRPy and GPRmax, R-based RGPR, and GPRViewer and GPR Process (Plattner, 2020; Warren et al., 2016; Huber & Hans, 2018; Conyers & Lucius, 2017). When using a GPR system that actively filters the data as it is collected, it is extremely important to not use default settings without considering their implications. Over filtering can lead to the complete removal of subsurface objects from the image (Utsi, 2017). To account for errors in data collection the GPR data processing sequence shown in Figure 9 includes, but is not limited to, band-pass filtering, dewow, time-zero corrections, filtering, and gains.

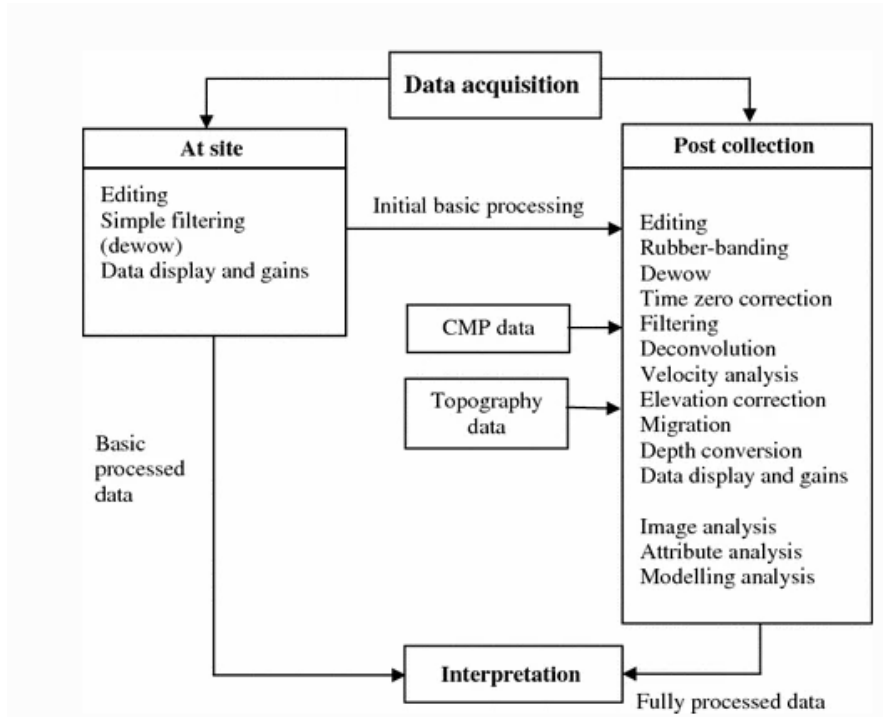


Figure 9: A typical GPR data processing and analysis sequence (Cassidy, 2009; Economou et al., 2015)

Time zero (Tz) removal is the first data processing step that should be taken for all surveys. If this is not performed, the depth measurements are overstated by the value of Tz. Tz is a measurement of the difference between the time the first signal is transmitted and when it is received, also known as the first zero crossing of the signal. This difference may occur due to the distance between the transmitting and the receiving antennas, the heterogeneity of the material, the temperature difference between the equipment and the air temperature, unstable electronics, and differences in cable lengths (Al-Qadi et al., 2010; Cassidy, 2009; Economou et al., 2015; Jol, 2008; Oberröhrmann et al., 2013; Olhoeft, 2000; Utsi, 2017). Figure 10 shows an example of a time vs. amplitude plot before and after time zero removal. Though there is no single method to account for this residual value and many studies have been performed to try and find the best approach, most manufacturers have a recommended method that is done either automatically or by a designated processing software (Angelis et al., 2019; Annan, 2015; Benedetto et al., 2017; De Pue et al., 2016; Diamanti et al., 2018; Dinh et al., 2018a, 2018b, 2019; Ernenwein, 2006; Kaufmann et al., 2018; Koyan et al., 2018; Rasol et al., 2018; Viriyametantont et al., 2008; Yelf, 2004; Zadhoush & Giannopoulos, 2022).

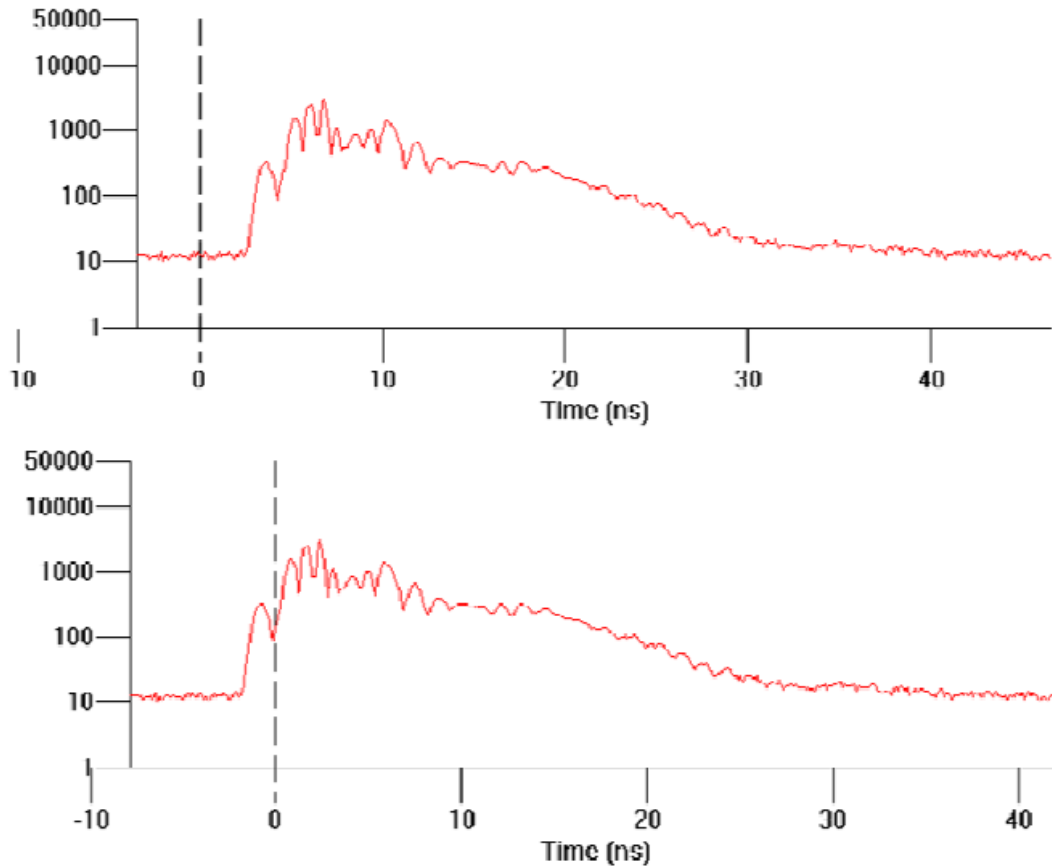


Figure 10: A time (ns) vs. signal amplitude plot before (above) and after (below) the time zero removal (Dojack, 2012).

Gains are a time-varying function used to enhance a profile that has been affected by signal decay. They are used in situations where the signal attenuates as it permeates further into the material, resulting in a profile that lacks detail passed a certain depth. The two most common types are linear gain, also known as Automatic Gain Control (AGC), and exponential gain, also known as Spreading & Exponential Compensation (SEC). When AGC is used, a constant gain is applied to all of the data. This is typically not preferable outside of low-frequency applications as it can over-amplify the signal, particularly along the top of the profile. When SEC is used, an increasing amount of gain is applied as depth increases. This is often the preferred method as signal attenuation is typically exponential and it is less likely to over-amplify the signal (Annan, 1999 and 2005; Dojack, 2012; Fisher et al., 1996; Geophysical Survey Systems, 1996; Neal, 2004;

Sensors and Software, 1998; Yilmaz, 1987 and 2001; Young et al., 1995). Figures 11 and 12 show an example of a profile before and after the application of AGC and SEC respectively.

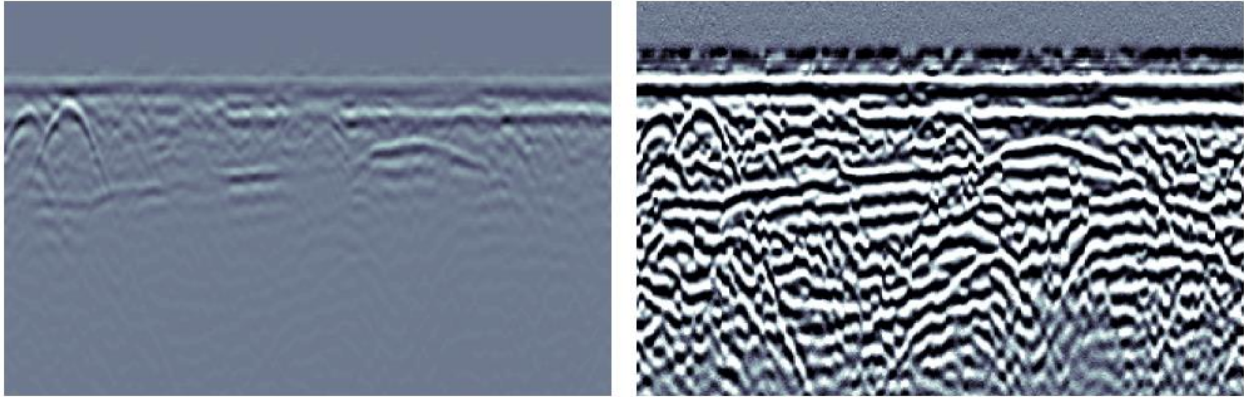


Figure 11: A profile before (left) and after (right) application of AGC. Dewow has been applied to both profiles (Dojack, 2012).

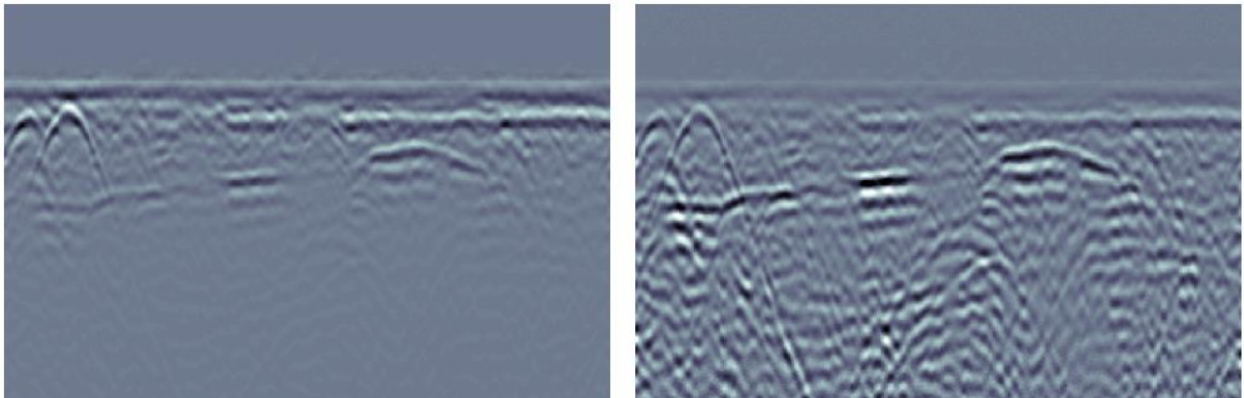


Figure 12: A profile before (left) and after (right) application of SEC. Dewow has been applied to both profiles (Dojack, 2012).

Filtering is the term for mathematically altering individual reflections to enhance or remove certain features and noise. There are two types of filters, time and spatial. Time filters, like dewow, are applied sequentially and alter the vertical profile. Spatial filters, which are used to mute certain reflections, are applied adjacently, and alter the horizontal profile (Economou et al., 2015; Neal, 2004). The term dewow is used to describe the process of removing the low frequency harmonics including the initial signal component and the “wow”. The ‘wow’ is the effect of signal saturation of the receiving antenna. Though methods of dewowing can and should be used in nearly all data

processing, they can cause reverberations which can be resolved using time-varying low-cut and high-pass filtering (Battista et al., 2009; Economou et al., 2015; Dojack, 2012; Neal, 2004; Sensors and Software, 1998). The before and after effects of applying dewow are shown in Figure 13, it is recommended that dewow be applied to all data sets to improve clarity and accuracy.

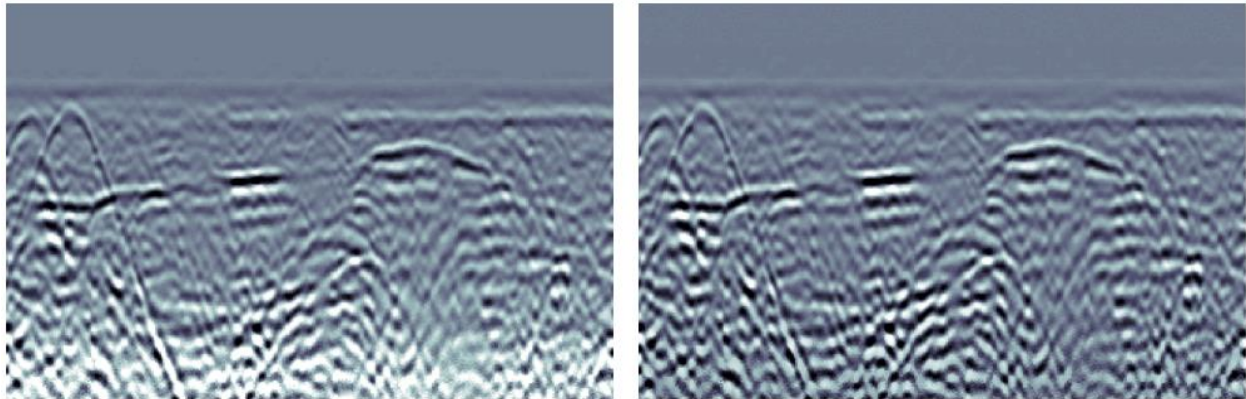


Figure 13: A profile before (left) and after (right) a dewow filter is applied. Gain has been applied to both profiles (Dojack, 2012).

Band-pass filtering is used to remove false noise or signals whose frequency is outside of the survey range. The numerical identifier of an antenna is its peak frequency, but the frequency range will either be clarified in the equipment's technical details or can be calculated using $0.5 - 2F$, where F is the peak frequency (Utsi, 2017). Thus, band-pass filtering is an effective way to refine data without manipulating the data values. Figure 14 is an example of a profile before and after a band-pass filter is applied. The difference in shading shows how certain features were mistakenly overemphasized before filtering. One technique for this is time-varying band-pass filtering which suppresses the noise outside of a specified band (Bradford & Wu, 2007; Economou & Vafidis, 2010; Schimmel & Gallart, 2007).

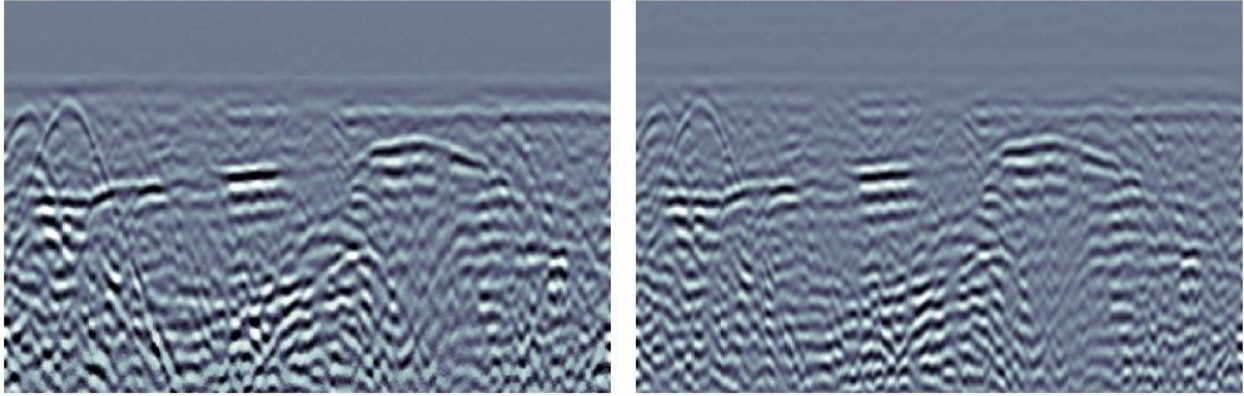


Figure 14: A profile before (left) and after (right) a band-pass filter is applied. The profile has a peak antenna frequency of 400 MHz, with a filter range of 200 - 800 MHz. Gain and dewow have already been applied to both profiles (Dojack, 2012).

Additional data processing techniques include but are not limited to the following. Time and frequency analysis, also known as spectral decomposition, is used to remove wavelet overprint from data allowing for a better representation of thickness variation in a profile (Ban, 2004; Bradford & Wu, 2007; Economou & Vafidis, 2010). Deconvolution, which decreases the duration of the dominant wavelet to remove repetitive reflections, but it relies on several unrealistic assumptions, so most research on the topic recommends against its use (Annan, 1999; Conyers, 2004; Chahine et al., 2011; Dojack, 2012; Economou et al., 2012; Economou & Vafidis, 2011, 2012; Schmelzbach et al., 2011; Xia et al., 2004). Velocity analysis and migration work to collapse hyperbolas into single points to aid in positioning linear objects (Berard & Maillol, 2007; Bradford, 2008; Brown et al., 2009; Pipan et al., 1999; Sena et al., 2006; Sensors and Software, 1999; Utsi, 2017). Attribute analysis is used to help interpret GPR sections and contribute to the expression of the data's reflectivity, amplitude, frequency, and phase relationships (Dojack, 2012; Economou et al., 2015; Massa et al., 2005; Pipan et al., 2001; Spanoudakis, 2007; Vafidis et al., 2007).

3.2 | History and Development of Ground Penetrating Radar

Throughout the history of GPR, the driving force for innovation and equipment development has been to test and improve its potential applications. Christian Hulsmeyer's Telemobiloscope, patented in 1904 and used to prevent ship collisions, is considered the first invention of Radio Detection and Ranging (RADAR) type technology. Due to the short range of the equipment and its few applications at the time, further progress was not a priority (Ender, 2002). By the time of the First World War, the technology necessary to measure and control short pulses of radio energy had been developed and the first radar systems were made (Watson, 2009). The first recorded use of ground penetrating radar for civil engineering purposes was in 1956 as a method of surveying water tables in the Egyptian deserts (El-Said, 1956). To perform this study a radio receiver was placed at a known distance from a transmitter, which allowed El-Said to measure the delay of the wave reflected from the water table compared to the direct wave from the transmitter to the receiver (Rasol, 2021). This approach successfully located the water table and remains similar to the current methods used (Benedetto & Pajewski, 2015). After pilots observed what they thought to be radar errors while attempting to land on the Greenland ice sheet, the next stage of GPR research began. What they had experienced while calculating the distance to the surface were not mathematical errors but were exaggerated measurements as their radar had penetrated the ice rather than being reflected off it. This discovery led to work by Waite and Schmidt in 1961 to image the landmass below this ice sheet (Waite & Schmidt, 1961). Following the success of imaging through the ice, researchers began to test its potential on other ground surface materials (Annan, 2003).

In 1970 as the potential for GPR as a non-invasive subsurface investigation technique grew, Rex Morey founded Geophysical Survey Systems Inc (GSSI), which created the first commercially available GPR system (Morey, 1974). The new accessibility of GPR accelerated its development

and application to academic and industrial practices. With the increased public and private sector demand, research on how to gauge and improve its accuracy became equally important as research on its potential applications. Over the next three decades, numerous studies have continued to test and develop the capabilities of GPR. Table 4 is an approximate timeline of the research and development of GPR.

Table 4: Overview of research and development of GPR from 1973 to 2000

Year	Author(s)	Article Title	Description
1973	(Phillips et al., 1973)	Apollo Lunar Sounder Experiment, in Apollo 17: Preliminary Science Report	Studies were performed using the data collected by NASA’s implementation of GPR on the Apollo 17 mission to examine the electrical properties of the lunar subsurface compared to the previously studied glaciers.
	(Simmons et al., 1973)	Surface Electrical Properties Experiment, in Apollo 17: Preliminary Science Report	
1975	(Olhoeft, 1975)	The Electrical Properties of Permafrost	A study on the correlation between the electrical conductivity and dielectric polarization of geological materials which was then used to inform the early understanding of how environmental factors influence GPR signals.
1976	(Annan & Davis, 1976)	Impulse Radar Sounding in Permafrost	A study on the use of GPR in the Arctic, one of the many applications of it explored by the Geological Survey of Canada to investigate the potential for building oil pipelines through the permafrost environment of the Canadian Arctic.
	(Watts & England, 1976)	Radio-echo Sounding of Temperate Glaciers: Ice Properties and Sounder Design Criteria	

Table 4 Continued: Overview of research and development of GPR from 1973 to 2000

Year	Author(s)	Article Title	Description
1978	(Dolphin et al., 1978)	Radar Probing of Victorio Peak, New Mexico	The Stanford Research Institute explored the archaeological applications of GPR in their work at Victorio Peak, New Mexico. GPR was able to aid the excavation process by identifying voids and irregular features up to 400 feet deep.
1981	A-Cubed Inc. and OYO Corporation were founded in 1981 as rivals to GSSI in the commercial development of GPR.		
	(Owen, 1981)	Cavity Detection Using VHF Hole-to-Hole Electromagnetic Techniques	A study by the US military to locate underground tunnels using the GPR borehole method.
	(Coon et al., 1981)	Experimental Uses of Short Pulse Radar in Coal Seams	A series of experiments using short pulse radar on coal seams determined that the technology could be used to probe coal seams prior to mining excavations.
1982	(Ulriksen, 1982)	Application of Impulse Radar to Civil Engineering	The foundation of civil engineering applications of GPR was established in this early study of its success in roadway investigations and utility mapping.
1983	(Benson et al., 1983)	Geophysical Techniques for Sensing Buried Wastes and Waste Migration	The work covered in Benson et al., 1983 & 1984, outlined the approach to using GPR to monitor groundwater and buried waste migration. The growing interest in the use of GPR to find buried waste and contaminants, as well as other environmental initiatives by the EPA, created a strong commercial driver for the development of GPR.
1984	(Benson et al., 1984)	Groundwater Monitoring: a Practical Approach for a Major Utility Company	
1987	(Olsson et al., 1987)	Cross hole Investigations - Results from Borehole Radar Investigations	GPR borehole methods studied as a potential resource to utilize as a noninvasive resource for monitoring nuclear waste disposal.
1988	Peter Annan founded Sensors and Software Inc. to commercialize the PulseEKKO technology which was initially developed by A-Cubed Inc.		
	(Annan et al., 1988)	Radar Sounding in Potash Mines: Saskatchewan, Canada	A comprehensive study by the Geological Survey of Canada confirmed that GPR could be accurately used to survey dry salt mines with low electrical conductivity.

Table 4 Continued: Overview of research and development of GPR from 1973 to 2000

Year	Author(s)	Article Title	Description
1990s			GPR processing developed rapidly with improvements in computing capabilities and technology throughout this decade. New companies, such as Mala Geosciences in Sweden and ERA Technology in the UK, were formed as the adoption of GPR in academia and industry continued to grow. Commercial product development moved towards lower frequency GPR units with full digital recording capabilities (Annan, 2003 & Rasol, 2021).
1992	(Doolittle & Asmussen, 1992)	The years of applications of ground penetrating radar by the United States Department of Agriculture	As the need for information on samples grew rapidly, the United States Department of Agriculture investigated the use of GPR to determine soil properties and classifications to greater depths than previously possible.
	(Maijala, 1992)	Application of Some Seismic Data Processing Methods to Ground Penetrating Radar Data	Various digital seismic data processing methods, such as one-dimensional seismic modeling, were adapted to work with GPR techniques like multi-fold data acquisition.
	(Annan & Chua, 1992)	Ground Penetrating Radar Performance Predictions	
	(Fisher et al., 1992)	Acquisition and Processing of Wide-Aperture Ground Penetrating Radar Data	
1993	(Gerlitz et al., 1993)	Processing Ground Penetrating Radar Data to Improve Resolution of Near-surface Targets	Imaging resolution of objects close to the surface improved using digital data processing.
1994	(Goodman, 1994)	Ground-penetrating radar simulation in engineering and archaeology	Advancements were made in archaeological and environmental applications due to improvements in GPR data simulation and processing.
	(Brewster & Annan, 1994)	Ground-penetrating radar monitoring of a controlled DNAPL release: 200 MHz radar	
1995	(Zeng et al., 1995)	Comparison of ray and Fourier methods for modeling monostatic ground-penetrating radar profiles	Projects with a focus outside of GPR applications were developed, such as these which studied tools for the quantitative analysis and two-dimensional numerical simulation of GPR.
	(Cai & McMechan, 1995)	Ray-based synthesis of bistatic ground-penetrating radar profiles	

Table 4 Continued: Overview of research and development of GPR from 1973 to 2000

Year	Author(s)	Article Title	Description
1996	(Jol et al., 1996)	Digital Ground Penetrating Radar (GPR): A New Geophysical Tool for Coastal Barrier Research (Examples from the Atlantic, Gulf and Pacific Coasts, U.S.A.)	GPR was developed for use as a method of studying the internal features of coastal land barriers by surveying geological strata layering.
	(Redman et al., 1996)	Borehole radar for environmental applications: selected case studies	Further work on environmental applications of borehole GPR was developed, including improvements on previous work and a collection of case studies.
	(Roberts & Daniels, 1996)	Analysis of GPR polarization phenomena	Interest in the nature of the radar pulses led to the analysis of polarization effects within GPR datasets using early three-dimensional numerical simulation.
1996	(Grasmueck, 1996)	3-D ground-penetrating radar applied to fracture imaging in gneiss	Advancements in data processing allowed for the efficient processing and management of large data sets, making it more accessible to map and create three-dimensional models based on GPR surveys.
1997	(Annan et al., 1997)	Maximizing 3D GPR Image Resolution: A Simple Approach	
1999	(Bergmann et al., 1999)	A simplified Lax-Wendroff correction for staggered-grid FDTD modeling of electromagnetic wave propagation in frequency-dependent media	Continued work on utilizing computer algorithms to design three-dimensional modeling techniques improved with improved computing power. Research on this tested the models against prior experimental observations.

Over the last two decades, GPR technology and research have developed rapidly due to increased commercial demand, improved computing power, and standardized equipment operation and management. Notable works in data processing techniques include advancements in 3D modeling and reconstruction, methods of automatic detection using machine learning, and integrated GIS mapping (Kim et al., 2021; Asadi et al., 2019; Liu et al., 2020; Tong et al., 2020; Mertens et al., 2015; Kim et al., 2019; Feng et al., 2021; Yamaguchi et al., 2020). Among the technological developments, researchers have found that implementing multi-antenna systems and

array multi-channel antennas allows for multiple data profiles to be collected at once, saving time and improving the continuity of 3D data sets (Gabryś & Ortyl, 2020).

3.3 | Applications of Ground Penetrating Radar

Scientific use of GPR began with the study of its geological and hydrogeological applications, but many new areas of civil engineering have applied it since its initial development. These areas include heritage site investigations, construction and land development operations, and infrastructure quality control and maintenance. This technology is valuable to many fields of study because it allows for non-destructive, accurate, and efficient testing and typically requires minimal staff and equipment to operate.

3.3.1 | Geology and Hydrology

Using GPR to survey geologic and hydrologic features creates a more accurate map of soil strata than methods like soil coring that only represent the features present at the precise location sampled. In a 1991 study by Beres & Haeni, they found that even with little to no data processing, GPR profiles of soil strata below plain ground or freshwater bodies could be used as high-quality qualitative data for hydrogeologic studies. With or without precise depth and thickness measurements, using GPR to profile layers of subsurface soil and rock prevents the unnecessary destruction of natural features.

As a state with many significant freshwater sources, Georgia has a responsibility to maintain and protect its aquifers and rivers. GPR is a valuable resource for this, and it can be applied to locate water tables, measure soil water content, and monitor groundwater. GPR can be used as a noninvasive method to determine the elevation of shallow water tables, how saturated the underground pores are, and the flow path of the water (Annan, 1991; Bentley & Trenholm, 2002; Doolittle et al., 2006; Harari, 1996; Lambot et al., 2008; Nakashima et al., 2001). A study

performed in Spain using GPR to measure the depth of a water table found that it produced a strong reflection through fractured granite but was nonvisible through heavy clay (Mahmoudzadeh, 2012). This observation is significant because granite and heavy clay are two common materials in Georgia, and both need to be considered when designing a GPR survey. GPR can mathematically estimate soil water content, bulk density, and stiffness using the relationship between the wavelength velocity through a material, its dielectric permittivity, and the volumetric properties of soil components (Abdelmawla & Kim, 2020; Tihey & Kim, 2020; Chanzy et al., 1996; Huisman et al., 2003; Klotzsche et al., 2018). This use applies to various types of land surveys, precision agriculture, and pavement design and monitoring. Furthermore, it is important to monitor the groundwater and other substances in and around aquifers to avoid potentially permanent contamination and damage to a water supply. GPR can detect and monitor groundwater contamination by detecting where there are sudden or unexplained changes to the material properties due to differences in signal attenuation and wavelength velocity (Benson et al., 1983; Benson & Pasley, 1984; Iwasaki et al., 2016; Porsani, 2004).

Throughout its history, the geologic makeup of the earth has been manipulated by long-term events such as rising and falling sea water levels, sustained wind, and shifting tectonic plates. Because of this it is helpful to study how landscapes have developed over time to prepare for future needs brought on by the changing climate. An early step in this process is to observe how soil properties have differed throughout history, which can be done by using GPR to image soil strata and detect cracks in rock slopes (Rees-Hughes et al., 2021; Suyemoto & Toshioka, 1955). Identifying cracks in rock slopes is beneficial because it is a common cause of a ground collapse. GPR has proved valuable in the growing science of paleoseismology, the study of old earthquakes, by mapping variations in soil properties and identifying cracking (Wald & Scharer, 2015). The

focus in this field is on studying historic earthquakes to better understand where they occurred and how large they were to design infrastructure capable of withstanding similar events in the future. In this field, GPR can provide clear subsurface images of faults, folds, and fissure fill without requiring direct observation via excavation, replacing the traditional trenching methods to identify the exact location and history of the fault (Gross et al., 1999; Salvi et al., 2003).

One of the most popular applications of GPR throughout its history and development is mining and analyzing mineral deposits. In these scenarios, GPR is used to locate precious metals, coal seams, salt deposits, and potential hazards. GPR is a standard exploration tool for surface mineral evaluations because it can reach depths over 131.2 ft (40 m) in areas with favorable electrical properties, save time and money by removing the need to use expensive and/or explosive excavation equipment, and is typically easier to transport to the remote areas under observation (Davis & Annan, 1989; Francke, 2012; Ralston, 2000; Rubin & Fowler, 1978). The 1974 study on electromagnetic reflections in salt deposits by Rudolf Thierbach is an example of the early work that has initiated decades of research on the use of GPR in mining. Since solid salt does not conduct electricity and has an RDP of 3-15, signals have a slow attenuation rate and can reach a greater depth than in many other subsurface materials. These conditions allowed Thierbach to delineate the salt deposit boundaries and locate pockets of conductive materials like clay in and around it using a relatively simple pulse transmitter. Being an ideal substance to work with, scientists and engineers have continued to perform increasingly comprehensive studies on salt deposits and salt-contaminated soil throughout the evolution of GPR. These include Grégoire et al. (2003), Gundelach et al. (2013, 2018), and Rejšek et al. (2015). A 1992 study by Olsson et al. compared a GPR survey with a geological and geophysical survey of fracture zones in crystalline rock. Though the 20-60 MHz frequency antennas were only able to reach a resolution depth of 3.3 - 9.8 ft

(1-3 m), the comparison showed that the identified features were of hydrogeological significance and matched the observations of the other survey. This confirmation is significant because it offers GPR as a way to survey materials in crystalline rock without the risk of irreversible damage being done to the surrounding area if an excavation was attempted (Olsson et al., 1992).

3.3.2 | Historical and Investigative Site Surveys

Ground penetrating radar is a valuable resource for heritage and investigative site surveys because it can identify potential dig sites before excavation and accurately survey areas that should be left undisturbed (Lohonyai, 2015). In a study on applications of remote sensing in forensic investigations, GPR reduced the amount of time lost at sites where there was nothing to find and allowed surveyors to avoid costly excavations that could risk destroying evidence (Davenport, 2001). For surveys performed in historical locations such as the El-Maghtas site in Jordan, studies determined that GPR can successfully identify buried infrastructure, such as walls, pottery pipes, and water systems and channels (Abueladas, 2020). GPR can also be used to study historical buildings, like in a 2015 study to assess the structurally significant columns, walls, and floors of the Santa Maria del Mar to help inform how to restore the ancient church properly (Perez-Gracia, 2015). An application of GPR that has brought significant attention to itself in recent years is its use in surveying cemeteries and former Indian residential schools to find unmarked burial sites (Peters, 2022). Like in its original archaeological applications, these surveys apply GPR to locate subsurface voids and anomalies that can identify unmarked graves without disrespecting cultural burial traditions (Vaughan, 1986; Kunze, 2022). Additionally, GPR is a valuable tool in clearing civilian areas of buried explosives. Work on the ‘TIRAMISU: Toolbox Implementation for Removal of Anti-personnel Mines Sub-munitions and UXO’ research project found that GPR with

integrated metal detection devices improves the productivity and safety of investigations and is adaptable to many types of terrain and ground cover (Nuzzo et al., 2014).

3.3.3 | Locating and Mapping Utilities

A frequent use of GPR for municipal purposes is to locate mapped and unmapped utility lines. This application is significant because GPR is effective for finding metallic and nonmetallic objects such as pipes, drums, tanks, cables, and other underground features. During the design process, especially while working in developed areas, engineers rely on utility maps to avoid and accommodate major waterways, sewers, gas lines, and electric cables (Sărăcin, 2017). If not considered in the design, it is even more critical for these objects to be mapped before breaking ground to avoid unnecessary delays or costly repairs (Plati & Dérobert, 2015). Before geotechnical work began for the design and construction of the Line 4 subway tunnel in São Paulo, Brazil, GPR was used to map utilities and existing infrastructure along the route. Damage to preexisting utilities can put human lives at risk, and damage to surrounding foundation columns or piles can have extensive consequences, particularly in dense urban areas like São Paulo. The survey data determined the locations and approximate depths of the utilities surrounding the proposed tunnel, and helped to avoid any potentially dangerous accidents (Porsani, 2012). A GPR survey to locate utilities was performed in 2010 along the intended route of the M-29 transmission line in Yonkers, New York, to try and avoid common expensive construction conflicts. The survey located both established and previously unmapped utility lines, and the project was able to proceed without being derailed due to repairs or redesigns, which on other projects typically cost them significantly more money than the cost of the GPR survey (Mooney, 2010). Following its success in finding buried pipes, GPR has developed into an effective method of detecting burst pipes and water leaks.

GPR can locate these leaks by identifying voids in the soil surrounding pipes and irregular depth measurements caused by changes to the soil's dielectric constant (Abouhamad et al., 2016).

As the commercial interest in using GPR to locate objects such as buried pipes have increased, so has research on improving the scope and clarity of results. Experimental results for a project introducing the use of discrete wavelet transform (DWT) to filter and enhance the GPR data were successfully able to differentiate between and show multiple pipes of different materials and horizontal locations within one profile image (Ni et al., 2010). Additionally, enhanced computer programming capabilities have improved how well raw GPR data is processed. A recent study used similar processes with improved computer power to find the most likely direction and radius of previously surveyed pipelines within a controlled error of 5% (Zhou et al., 2022).

An increasingly popular application of GPR utility surveying is to map the locations of identified objects in a geographic information system (GIS) map. Using the data from a GPR unit's locating device, whether a manual measurement or a precise GPS location, the GIS system can create an adaptive, growing map of data points (Li et al., 2015; Tabarro et al., 2017; Yuan & Cai, 2020). Though it is particularly popular for utility mapping, GIS and GPR can be used together to track nearly any subsurface objects of interest.

3.3.4 | Concrete

In addition to mapping underground objects, GPR's nondestructive nature means that it can be used for inspecting embedded reinforcement and areas of concern in hardened concrete. In these scenarios, GPR replaces labor-intensive, dangerous, and often inaccurate quality control methods (Lohonyai, 2015). Using GPR before cutting, coring, or breaking a concrete slab for new build construction or renovation projects can prevent damage and delays. In slabs, GPR can identify subsurface objects like steel rebar, post-tensioned cables, pipes, and electrical wiring encased in

conduits. Cutting into any of these could cause costly damage to machinery, threaten the structural integrity, and for post-tensioned cables and wiring, create potentially deadly safety hazards for those working on-site (Penhall, 2022). During precast concrete inspections, GPR can measure the concrete cover depth, the reinforcement location, and section thickness. However, the quality of results is lower for thick columns and members with dense steel mesh reinforcement that the signal cannot pass through (Goulias & Scott, 2015).

Studies have found that in bridge decks, GPR can be used to map corrosion, identify moisture infiltration and delamination, locate damage, and model the internal construction of structural elements (Abouhamad et al., 2017; Alani et al., 2013; ASTM, 2008; Benedetto et al., 2012; Chung et al., 1992 and 1993; Clemeña, 1983; Goulias & Scott., 2015; Hong et al., 2015; Hubbard et al., 2003; Hugenschmidt & Mastrangelo, 2006; Kalogeropoulos et al., 2011; Lai et al., 2013; Lubowiecka et al., 2009; Maser, 1996; Parillo et al., 2006; Stryk et al., 2015; Tarussov, 2013; Villain et al., 2012). Unrelated to the concrete in a bridge structure, GPR has also been studied as a way to detect existing and filled scour holes near bridge piers (Placzek & Haeni, 1995; Chang et al., 2004). GPR can also be used to inspect organic material below a concrete cover as long as it does not have dense steel reinforcement. This use can be applied to locate subsurface voids and deterioration in dikes, dams, and retaining walls (Carlsten et al., 1995; Hugenschmidt & Kalogeropoulos, 2009; Xu et al., 2010).

3.3.5 | Roadway and Pavement Condition Assessment

A widely studied use of GPR is inspecting pavement material properties and condition (Lohonyai, 2015). GPR can be a measurement tool for roadway types including flexible and rigid paving, with or without reinforcement. GPR is mostly used for measurements at the project scale, where a detailed assessment of a previously selected section of roadway is done to identify and diagnose

its specific needs. Otherwise, GPR is performed at the network scale, where many measurements are processed to determine problematic roadway sections needing maintenance, repair, or reconstruction. Applications of GPR at the project scale include determining the thickness of asphalt pavement layers, the thickness of concrete pavement layers, the thickness of sub-base layers, the position of the reinforcement in concrete pavement, any potential debonding and delamination of pavement layers, and heterogeneity of a pavement. Research applications of GPR include determining the condition of concrete pavement reinforcement, depth of visible cracks on the pavement surface, location of cracks originating along the bottom of the pavement layer, sub-asphalt areas damaged by water and clayey soil infiltration, and difference in properties throughout distinct pavement layers (Abdelmawla & Kim, 2020, 2021; Bigman, 2018; Cao et al., 2007; Laitinen et al., 1996; Loizos et al., 2021; Rasol et al., 2022; Stryk et al., 2015). Without GPR, methods of determining the properties and thicknesses of a pavement's layers are limited and rely on the assumption that the properties will be homogenous. These methods rely on resources such as pavement layer design information, which typically assumes consistent properties throughout the section, or pavement cores, which require destructive material collection methods and only represent a small portion of the roadway (Goulias & Scott, 2015). The limitations of these two methods encourage the use of GPR as it requires minimal road closures and traffic delays and does not rely on the assumption that the pavement was placed the exact way it was designed.

3.4 | Training and Education of GPR Technology

There is minimal nonproprietary GPR training information available to those learning how to operate the technology for applications outside of rail track and pavement condition monitoring. From June 2015 to January 2018, the United States Department of Transportation Federal Railroad Administration performed a three-year study to develop a guide to *Ground Penetrating Radar*

(GPR) Technology Evaluation and Implementation for North American Railroads (Basye et al., 2020). This report was created to guide those interested in using GPR systems installed on railcars to track the condition and degradation of tracks. Though it is a valuable resource for those in the rail industry in North America and offers advice concerning general data interpretation, it lacks the broad applicability needed by municipalities that could use GPR to provide a wide range of services. The majority of GPR resources produced at the state government level are in relation to pavement thickness measurements. While this work is more broadly applicable to municipalities than railroad monitoring, it does not encapsulate the training needs of local governments.

The Minnesota Department of Transportation has been developing research literature on GPR since at least 2007, when the *Implementation of Ground Penetrating Radar* report was published (Cao et al., 2007). This report demonstrates the capabilities and limitations of GPR use on local roads by giving a brief overview of GPR equipment, introducing potential applications, and assisting in determining if site conditions are right for use. This work was followed up by a 2010 study, *Incorporating GPS and Mapping Capability into Ground Penetrating Radar (GPR) Operations for Pavement Thickness Evaluations* (Lebens, 2010). This study is an improvement upon the previous work and was done to create a manual to explain GPR operations and data collection using GPR with GPS and GIS, and create a new standardized method of data collection and reporting for the State. In 2021, *Pavement Thickness Evaluation Using 3D Ground Penetrating Radar* was published as an additional work on GPR procedure methods by the MDOT (Khazanovich, 2021). Though each of these is similar to the intention of the current research with the Georgia APWA, they are limited to pavement thickness evaluation processes developed for a state with considerably different pavement design parameters. The 2014 Wisconsin Structure Inspection Manual includes a section on GPR but only discusses introductory systems information,

applications, and limitations of the technology and does not include guiding instructions (Wisconsin DOT, 2014). In 2015, Arkansas published a report on how to use GPR for pavement evaluation focused on how to apply GPR to measure pavement layer thickness (Hall, 2015). From the resources available on their website, it does not appear that any additional reports or guides on this subject have been made since. Upon initial review, similar manuals exist for the Departments of Transportation in Maine, Montana, and Florida, and none that have been found cover multiple types of applications (Mallick & Nazarian, 2007; Maser et al., 2011; Holzschuher, 2007).

3.5 | Conclusion

Through this preliminary review, it has been determined that there is a lack of publicly available comprehensive resources to guide the process of acquiring and operating a GPR system. The existing resources are either limited to specific applications and do not include information on selecting units, or are materials published GPR the manufacturers attempting to market their product. The problem with having informative material primarily provided by those marketing GPR units rather than public organizations is that the education and selection process is biased. GPR technology has significant potential to help agencies in their work, but it will not always be the best option of how to meet a group's financial and operational needs. It is important to have a way of informing this choice that is not influenced by potential profit. Additionally, for groups that do not need an upgraded system, having nonmanufacturer-made resources available is a way to avoid excess spending. Additionally, there is a lack of guiding resources that account for and describe how the many types of natural landscapes and environments throughout the state of Georgia influence the functionality of GPR surveys.

As noted by the 2021 FHWA article mentioned in section 2.2 there is nationwide interest in the development of knowledge-sharing platforms and resources on the best practices of

operating NDT like GPR. Because of this, the research and work prepared for this project have the potential to guide the development of similar resources in other states.

4.0 | PROBLEM STATEMENT

4.1 | Research Objectives

Provided proper user understanding and training, GPR is a valuable, yet often underutilized, resource for the types of subsurface investigations that are routinely performed by Public Works Departments. This research aims to determine the current knowledge and use of GPR by Georgia municipalities and develop a guide and curriculum on it for the American Public Works Association (APWA) of Georgia. The focus is on GPR as, despite its promising potential as a widely applicable tool able to meet the needs of a government at any level, there are barriers to its use. Therefore, this research intends to create a single system curriculum to assist with improving municipalities' familiarity with and understanding of GPR in an effort to increase their use of it. The curriculum will include a guide on detailing GPR technology, a curriculum on how to use it and interpret its data, and a decision matrix for determining how, where, and when to use different GPR types.

To accomplish this objective, the project will include six research tasks. First, a comprehensive literature review is performed to illustrate the development, applications, and use of GPR equipment. A survey, followed by individual interviews, is performed to better understand current GPR usage by municipalities and the current challenges to its use and adoption. Using the information gathered in each of the prior tasks, the initial guide and curriculum is developed to address the identified gaps in knowledge. The curriculum is evaluated and improved through the implementation of case studies with local municipalities in Georgia to illustrate various

applications and include the process of data collection, image analysis, and results. The project findings and outcomes are reported, followed by the delivery of the finalized guide and curriculum.

4.2 | Research Significance

GPR has gained widespread acceptance as a reliable geophysical surveying method that uses radar pulses to identify and image vertical deflections across subsurface areas. The technology has been practically used to image subsurface conditions at depths from ground-surface to 30ft or more depending on the unit's antenna frequency (range 10 MHz – 2.6 GHz) with lower frequencies able to reach greater depths. It has a diverse number of applications, such as locating current or abandoned water/sewer lines and buried utility vaults, perform condition assessments on pavement and concrete, and perform comprehensive geotechnical investigations. This project, specifically the curriculum, will help increase Georgia municipalities' GPR use and understanding.

One of the main reasons for GPR's increased popularity is the speed and accuracy with which data is captured compared to more traditional methods. Manual infrastructure asset location and condition assessments are necessary and often lengthy, invasive, and costly processes, which GPR can replicate in a more efficient, non-destructive manner. Despite this, and GPR becoming more cost-effective and accessible in recent years, it still remains an underutilized technology. If the technology was more widely adopted, cost savings to local governments could be realized through improved asset management and planning. This includes a more accurate record of utility line locations, preconstruction geotechnical explorations, determining the root cause of pavement cracking, and many other uses requiring subsurface analysis. Additionally, GPR can be used to help municipalities better manage their assets by allowing for more efficient long-term planning as an effective method of evaluating infrastructure conditions. This is significant as it has the

potential for sizable economic benefit to the municipality and reduces the risk of undetected and costly infrastructure failures.

5.0 | RESEARCH METHODOLOGY

The development of the general methodology, shown in Figure 15, is the phase in which the scope and goal of the research are outlined.

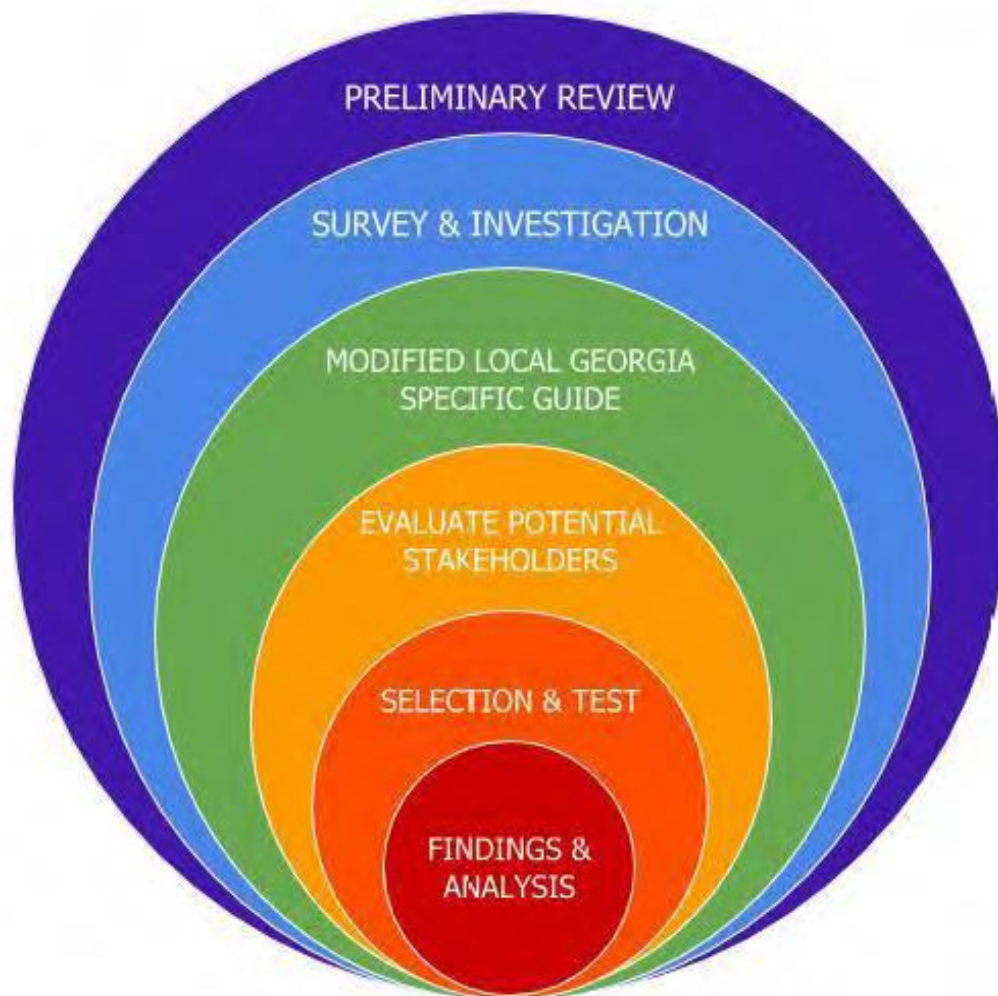


Figure 15: General Research Methodology (Nguyen, 2020)

To begin, a preliminary review is performed to understand the current applications and development of GPR and the types of training materials available for those conducting surveys at

the municipal level. Once the review was complete, a survey was developed to gather qualitative and quantitative data on various local Georgia governments' experiences with GPR. After the surveys, 10-15 virtual interviews were held to gather more in-depth information from survey respondents. Using the data collected in the preliminary review, surveys, and interviews, the next stage of the research developed a guide specifically designed for use by local Georgia governments. Several governments were then selected as stakeholders to participate in case studies to evaluate the curriculum and test the functionality of the guide. After completing the case studies, findings were analyzed and incorporated into finalizing the curriculum.

5.1 | Preliminary Review

A preliminary review of the use of GPR for tasks related to municipal services as well as the existence of curriculums on GPR for local governments was performed to define the concepts and goals of this research. The review outlined an array of GPR applications that were used to inform the survey questions and show different areas in which GPR could benefit local government work. The review covers the history and development of GPR as a way to better understand how the equipment has evolved, and which applications are regularly used versus those that are still being researched. Because of the technically challenging aspects of conducting GPR surveys, the review needed to include a section on the ways that these factors are influenced by operator behavior and material properties.

The investigation into the kinds of guiding curriculums for GPR users indicates that this study is warranted, as there is currently no such material made for those working within the constraints of a local government or municipality. Additionally, most existing GPR manuals are either provided by manufacturers for specific equipment or are outdated. GPR technology has the potential to be a valuable, multifunctional tool for local governments to use, and access to it would

be improved by the development of a curriculum that can teach interested parties about what it is and what it can do as well as how an agency in their position can implement it.

5.2 | Survey

A survey was developed and distributed to local Georgia government representatives to gain a better understanding of GPR use throughout the state. The survey's primary goal was to identify which municipalities currently own and operate their own GPR units, which use GPR through private contractors, and which are unfamiliar with the technology and its applications. After identifying the types of users across the state, the survey aimed to gather data on their applications of GPR, the challenges associated with its use, and the types of resources that would improve its implementation. The survey was distributed via email to all individuals on the Georgia APWA Roster as of September 30, 2022, and the Metro Atlanta branch of the APWA. This included a total of 685 contacts, representing 41 counties, 89 cities, 6 government organizations, and 51 private contractors.

5.2.1 | Survey Development

The survey, displayed in **Appendix A**, consists of 19 qualitative and quantitative questions separated into four generalized sections: General Agency Information, Agency Services and Budget, GPR, and Current GPR Users. The General Agency Information section asks for the name, title, and contact information of the respondents, as well as the name, population, and type of community that they represent. The population size choices were divided into four intervals: Rural (less than 2,500 people), Small (2,500 - 20,000 people), Mid-sized (20,000 - 75,000 people), and Large (greater than 75,000 people) (Dickey, 2019; Nguyen, 2020).

The next section asks for information concerning the Agency Services and Budget. The quantitative questions for this section ask for the agency's approximate total budget, and the

percentage of money and time dedicated to the following: Bridge Inspections, Dam Inspections, Pavement Maintenance and Repair, Locating and Mapping Utilities, and “Other”. The qualitative question for the section asks which of these services are provided by the agency.

The third section asks for information regarding the agency’s experience and interest in using GPR. The first question, “Is your local government familiar with ground penetrating radar (GPR)?” is included to establish the respondent’s familiarity with, and potential use of GPR. The four categories of familiarity to choose from are: Yes, we are familiar with GPR and currently own and operate our own unit(s); Yes, we are familiar with and use GPR; but the work is contracted with private consulting firms; Yes, we are familiar with GPR and its applications, but have not used it before; and No, we are not familiar with GPR or its applications. Identifying their degree of familiarity and use is important for data interpretation as those who own and operate their own unit(s) and those with no GPR experience have vastly different perspectives to contribute to this project. The following three questions polled the representative’s interest in adopting the use of GPR; whether they are interested, not interested, or currently using GPR for the common applications outlined by the preliminary review; and the services where they would expect GPR to reduce the current expense and effort required to execute them. Additionally, the section asked for feedback on the challenges and negative experiences they have had associated with GPR.

The fourth and final section is open only to those who selected their GPR familiarity as “Yes, we are familiar with GPR and currently own and operate a unit(s).” These questions were included to establish the parameters currently used to select GPR units and antennas, as well as the funding used to purchase them. The final two questions in the section asked how employees had been trained to use GPR, and if their agency had developed any resources to support the process of learning how to use the technology. These are included to assess whether or not there

are existing resources similar to the curriculum this program aims to create. The final question allows the respondent to provide any of the questions, comments, or concerns they may have about the project.

5.2.2 | Analyzing the Survey

Survey responses from representatives across Georgia were collected over four weeks. Out of the 71 responses recorded by the Qualtrics Online Survey Software, 38 provided the necessary participant information. These 38 responses represent 35 various cities and counties across the state. Out of the 38 participants, 30 completed the entire survey, and eight did not. The results of the survey data interpretation are described and represented graphically in Chapter 6.2.

5.3 | Interviews

Fifteen candidates were selected using survey data for further in-depth conversational interviews. The purpose of these interviews is to enhance the data extracted from the survey with a more detailed history of the respondent's experience with GPR. These interviews help inform how local Georgia governments use the ideas and applications discussed in the preliminary review and the reasons behind their opinions and choices concerning GPR. It is essential to consider what has and has not worked in the past and learn what types of practical tools this project can develop to make a valuable resource for communities.

5.3.1 | Interview Candidate Selection

Interview candidates were selected based on the quality of their survey answers, their frequency and type(s) of GPR applications, and any other unique features determined to be significant. Significant features include the challenges they associate with using GPR, previous negative experiences, the quality or relevance of their response to the final survey question regarding their comments, questions, and concerns about the project, and the population size and budget of their

jurisdiction compared to their method of GPR use. Candidates include five agencies from each of the following three categories: Those who own and operate a GPR unit, Those who hire private contractors for GPR surveys, and Those who have never used or are unfamiliar with GPR.

Of the survey respondents that own and operate a unit, interviews were requested with Forsyth County Water and Sewer, the City of Valdosta, the City of Statesboro, the City of Loganville, and the City of Monroe. Of those who work with GPR contractors, interviews were requested with the Brunswick-Glynn County Joint Water & Sewer Commission (JWSC), the City of Atlanta, the City of Marietta, the City of Gainesville, and Sumter County. Of those unfamiliar with GPR, interviews were requested with Fulton County Water and Sewer, the City of Warner Robins, the City of Lawrenceville, Peachtree City Sewer and Water, and the City of Oakwood.

Out of the fifteen, six accepted the interview requests. These are the City of Monroe, the City of Valdosta, the City of Gainesville, Forsyth County, the City of Atlanta, and the Brunswick-Glynn County JWSC. Additional interviews with Fayette County and Athens-Clarke County took place after presenting the project at the Georgia APWA Winter Certificate of Public Works Management (CPWM) conference. **Appendix B** includes a list of the interviewees and their contact information.

5.3.2 | Interview Questions

Candidates were asked questions to learn more about their local government's experience with and interest in using GPR. The guiding questions, which vary depending on their familiarity with and use of GPR, are included in **Appendix C**. These questions were developed to gather information on how local governments have made GPR accessible to themselves, what has limited their success or interest in using it, and which resources are the most relevant and necessary to include in the proposed curriculum. Each interview began by asking the candidate to describe the main responsibilities of their position. This is important to know to properly contextualize their answers

and to determine if they have the necessary experience. Following this question, there are three categories of guiding questions for each of the three candidate categories.

The first category is for local governments that personally own and operate a GPR unit. The first question for these (What motivated the decision to purchase a unit rather than hire a private contractor for the work?) is to determine the factors that have led communities to invest in their own GPR unit in addition to why they were generally interested in using it. The second question (What unit(s) do you own?) is the same as one of the survey questions, but since this question was left blank by a representative it is being asked a second time. This question is relevant to the project as it will help to identify trends in the types of equipment being marketed to and bought by local governments. The third question (What type of funding was used to purchase your unit(s)?) is included to learn more about how these groups were able to purchase a unit and provide the data necessary to make a funding matrix to include in the final curriculum. The fourth question (Who, or which department, within your organization, is responsible for operating the GPR unit(s)?) was selected to help inform how the agencies manage GPR use, training, and the types of quality control measures in place. The fifth and final guiding question for this interview category (What does your organization use GPR for?) is included to gather data on the types of GPR applications that they feel they could properly train employees for, and how satisfied they are with the process and results.

The second category of guiding questions is for local governments that hire private contractors for GPR surveys. This is an important group to learn from, as they consider GPR a useful tool for their work, but have some barrier in place that stops them from investing in their own unit and performing the work themselves. The first question (How frequently do you work with GPR contractors?) is to gauge the frequency of GPR use within the organization. If it is used

frequently on a diverse range of applications, they are more likely to be interested in investing in a GPR unit of their own than an agency that uses it infrequently. That being said, those that use it infrequently may be eager to learn how to operate a unit and lower the cost of using a GPR survey, as well as act as a valuable source on the types of limiting factors and challenges that the curriculum should address. This is followed by the second question (How much does this typically cost?) so that the cost of hiring a contractor to perform the surveys can be properly compared to the expense of purchasing a unit and training employees. This project aims to make the way that these services are performed more time and cost-effective, so if that is not achieved by using GPR, it should not be recommended. This question also provides an opportunity to ask what type of funding is used to hire contractors and if it is different from what can be used to purchase GPR equipment. The third and final question (Has your organization considered purchasing a GPR unit? Why or why not?) for this category is included in their interviews to provide more context for their choice to hire contractors rather than buy a unit.

The third category of guiding questions is for local governments that have never used, or are unfamiliar with, GPR. The first question (Are you interested in using GPR as a tool for surveying?) is to establish the representative's opinion and current knowledge of GPR as a resource. If they are unfamiliar with GPR or its applications, their response can help inform how to use the curriculum to introduce the technology. The second question (Has your organization considered using GPR in the past, but ultimately decided against it?) is asked because if they have considered using GPR, either with contractors or a personal unit, but ultimately decided against it, they can provide insight into their specific limiting factors and challenges associated with the use of GPR. The third question (In your survey response, you indicated that your organization would be interested in utilizing GPR for the following applications: ___) is made up of three parts: How

are these tasks currently performed; What are the costs and time spent associated with this method; and Is this method effective. This question is asked so that the curriculum does not recommend GPR be used if it is not an effective method of providing the service at this level.

5.4 | Developing a Guide to the Implementation of GPR by Local Georgia Governments

The next phase was to develop a curriculum on GPR for local Georgia agencies based on the needs identified in the interviews. The curriculum combines the academic information from the literature review with the experience and advice from the survey and interview data. The intention behind using both types of sources is to provide educational content that is both technical and applicable to agencies working with similar constraints. The curriculum serves as a Georgia-specific guide to using GPR for asset management and a resource with methods to effectively select, purchase, and operate a unit, introductory information on employee training, and how to access additional in-depth resources when necessary.

The guide is intended to help interested Georgia municipalities access GPR and implement the technology into their work. It provides this by serving three distinct purposes. First, to educate readers on GPR technology, how it works, and its applications to asset management. Second, to offer guidance for selecting and implementing the technology for particular applications. Third, to serve as a GPR resource regardless of the end-user's knowledge of the technology.

The review process is necessary to understand how the curriculum is received as a resource and whether or not it is a functional tool. Implementing a review of the work helps the guide better meet the needs of Georgia agencies by using the feedback to update and improve the material.

5.5 | Selection for Curriculum Review Case Study

The purpose of the case studies is to have communities with varying levels of GPR familiarity review and implement the guide and provide feedback on their experiences. The choice of

communities to include in the curriculum review case studies is based on population size, budget, and participation in the previous steps. Following the completion of the first draft of the guide, five agencies were identified as potential case study participants. Of these, the City of Monroe owns and operates a GPR unit, the City of Gainesville and the Brunswick-Glynn JWSC are interested in investing in in-house GPR operation, and the City of Atlanta and Athens-Clarke County would like to increase their use of GPR, but not invest in a unit at this time. Of the original five, three agencies agreed to participate in the curriculum review. These are the City of Monroe, the City of Gainesville, and Athens-Clarke County.

5.6 | Curriculum Review Implementation

Once the communities agreed to participate, the case studies were performed independently using the guide in **Appendix E** and the review form in **Appendix D**. The review's purpose is to learn how relevant and helpful the information is and where the curriculum can and should be improved. Participants give each chapter and section two scores, one for execution and one for relevance.

For the execution score, the options are 1 - Poor, 2 - Needs Improvement, 3 - Average, and 4 - Well Done. This score is for rating the quality and accuracy of each section regardless of its relevancy to the reviewer's work and interest in GPR. It is necessary to understand the quality of each section outside of the individual's needs because the guide is meant to help end users across a spectrum of GPR knowledge and experience. For the relevance score, the options are 1 - Irrelevant, 2 - Somewhat Irrelevant, 3 - Somewhat Relevant, and 4 - Relevant & Useful. This score is for rating the applicability of the section without considering the quality of work. Comparing the relevance and execution score identifies which sections are unnecessary, even if well done, which need more information, and which need to be improved. In addition to the usual chapter ratings, "Chapter 3: Best Practices & Decision Making" asks reviewers to score the execution and

relevance of Tables 3, 4, 5, and 6. These tables and decision matrices are supposed to be helpful, quick reference guides for the users. How users respond to these tools indicates how well the curriculum has achieved its intended goals.

Short answer questions followed the section-by-section execution and relevance scores. The question "Do you have any other helpful criticism/ comments/ requests related to this chapter" is included after each score table. The "General & Supplemental Information" and "Chapter 2: GPR Basics" sections have additional questions. For "General & Supplemental Information," these are "Are there terms that could be better defined?" and "Are there any terms that should be included in the acronyms or definitions?". The first question is to determine if any phrases in the guide's text or definitions page should be redefined to improve user understanding. The second question is to determine if there are terms that should be considered a fundamental definition and added to the reference sheet. If there are words that the reviewers find that they need to look up to contextualize other sections, searching the text is inconvenient and time-consuming compared to using a glossary. The additional question for "Chapter 2: GPR Basics" is, "Do the figures help explain concepts?". Chapter 2 in the guide includes many figures to try and help explain the information in the text in a visual format. Due to the complexities of how GPR works, it is crucial that these figures do not overcomplicate concepts or detract from the written explanations.

6.0 | RESEARCH FINDINGS

6.1 | Preliminary Review Findings

Using GPR to locate subsurface abnormalities is found to benefit asset management by improving construction coordination, improving preventative maintenance, increasing survey efficiency, and decreasing utility damages. There are no existing comprehensive resources for local governments on the concepts and use of GPR. Current resources on the selection and implementation of GPR are either provided for specific applications or by GPR manufacturers and retailers.

6.2 | Survey Analysis Results

Survey data and results were recorded through Qualtrics Online Survey Software. Of the 71 surveys started, 38 provided the required participant information. Of the 38, 30 completed the survey, and eight did not. In total, due to occurrences of multiple responses from the same agency, 26 complete responses were collected and considered. These 26 represent six counties, 16 cities, and four water & sewer authorities. Referencing Figure 16, the majority of responses came from agencies in mid-sized (20,000 – 75,000 people) communities, and no rural (< 2,500 people) communities participated in the survey. The survey data results represent eight large (> 75,000 people), 11 mid-sized (20,000 – 75,000 people), seven small (2,500 – 20,000 people), and zero rural (< 2,500 people) agencies. Figure 17 shows the distribution of respondents across the state.

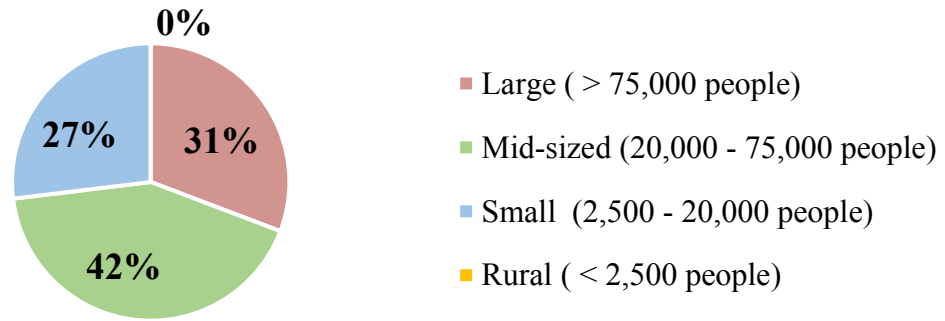


Figure 16: Distribution of Survey Responses by Population Size

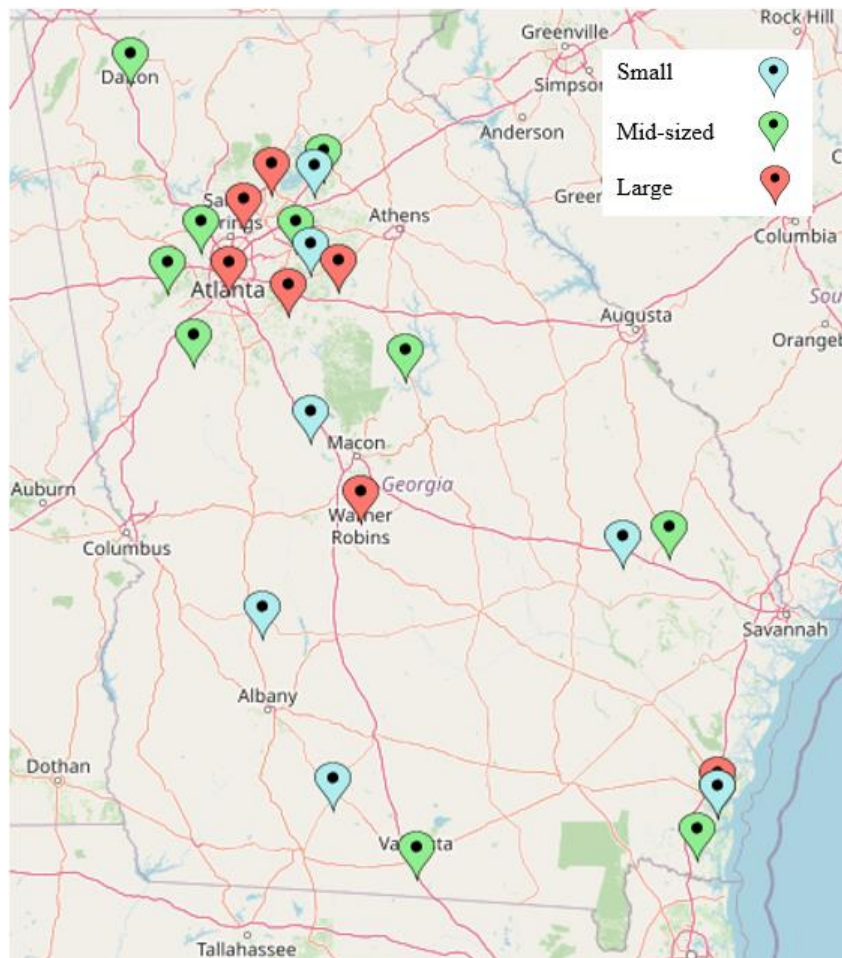


Figure 17: Map of the Survey Respondents by Population Size

Data analysis has identified inconsistencies that are a result of certain respondents classifying themselves as a city or county but completing the survey based on department-specific data. An

example of this is the results from the City of Warner Robins. The general fund budget according to the completed survey is \$3 million, but the published Fiscal Year 2023 Adopted Budget lists the general fund expenditures at \$53.8 million. Upon further review, based on the position title of the respondent as well as the Storm Water Drainage Enterprise Fund from the previously mentioned 2023 budget, it appears that the \$3 million represents the budget of the city's department of stormwater compliance rather than its general fund. Though the previous observation could be taken to mean that the survey should be applied to that department alone, the respondent included services performed by other departments working with different budgets in their list of "provided services". This does not make the survey data unusable, but conclusions should be limited to observations or correlations and not claims of direct causation. The inconsistencies are likely due to a combination of user error and unclear instructions, so interviews have been requested for those with noticeable discrepancies in their data.

6.2.1 | Agency Services and Budget

Only two out of the four questions in the agency services and budget section are included in the results. The two questions concerning the percentage of the general fund budget and the percentage of time allocated to various services did not provide conclusive data. These two questions are not to be considered in data interpretation as they yielded few responses, and those that answered them frequently used the same percentage for each service, indicating inconclusive results.

Seven of the eight local agencies serving large populations reported their general fund budget, and the category average is approximately \$92.3 million. Ten of the eleven local agencies serving mid-sized populations reported their general fund budget, and the category average is approximately \$41.4 million. Five of the seven local agencies serving small populations reported their general fund budget, and the category average is approximately \$10.4 million. More

information on this is included throughout the following sections, as budget alone does not serve as a conclusive measure of data.

The second question for respondents is “Which services does your local government provide for citizens? Select all that apply” with a list of services, that according to the preliminary review, can utilize GPR to improve accuracy, efficiency, or cost. The answers, shown in Figure 18, indicate that out of all agency categories, 73% of the total respondents provide utility locating services and pavement maintenance and repair. These are two of the most common applications of GPR, though pavement monitoring is less likely to be used in situations outside of formal research investigations. In all of the categories except pavement maintenance and repair, large agencies are the most likely to provide the service. This discrepancy is influenced by the fact that three of the eight respondents in the category are water & sewer authorities. Not counting these three, 80% of the large agencies report providing pavement maintenance and repair. Similarly, if the one mid-sized water and sewer authority is not considered, 100% of the county and city respondents in the category provide pavement maintenance and repair. There do not appear to be any services unique to the size of the agency. Of the 11 respondents that selected “Other” as a service, seven listed a variety of stormwater management services, including water & sewer, stormwater infrastructure, and storm drainage. Overall these seven are approximately 25% of all respondents, which suggests that the curriculum should include information on how GPR can be used in stormwater management.

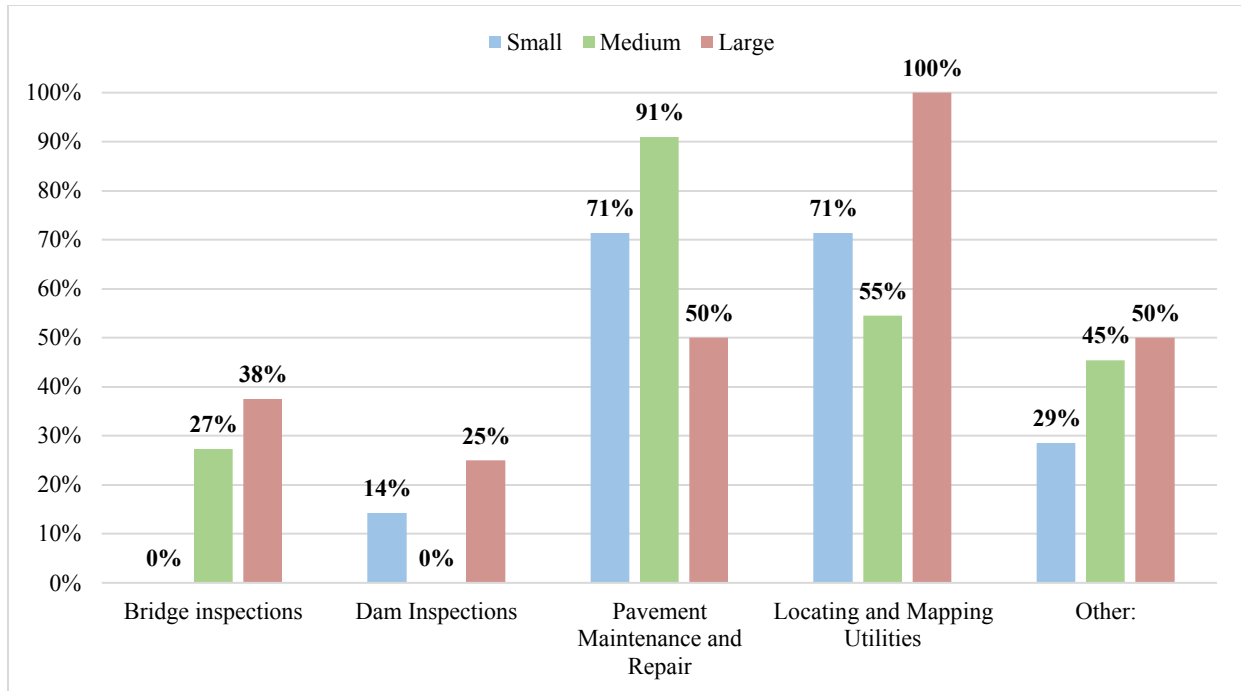


Figure 18: Services Provided by Respondents by Size

6.2.2 | GPR

The third section of the survey asks questions concerning GPR familiarity, use, and interest.

6.2.2.1 | GPR Familiarity

The first question, “Is your local government familiar with ground penetrating radar (GPR)?” has four response options to choose from. The first is for those who own and operate a unit within their agency, the second is for those who use private contractors for GPR surveys, the third is for those who know of GPR but have never used it, and the final is for those who have yet to be introduced to GPR and its applications. The intention behind establishing these classifications is to understand how agency size, budget, or type increase or decrease the likelihood of GPR familiarity. One of the intentions behind the question is to learn who, after learning about GPR as a resource, chose to implement it and who did not. The choice to not use it is likely based on either a lack of interest

in it or limited resources that make it inaccessible. As detailed in Figure 19, 15% of all respondents were unfamiliar with GPR or its applications, and 19% own and operate their units.

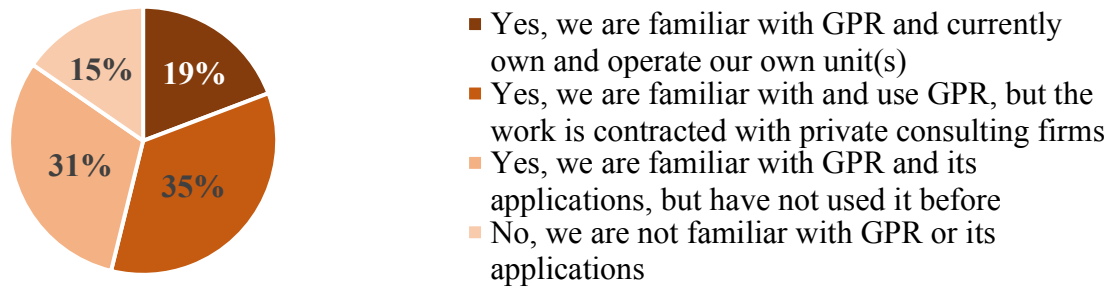


Figure 19: GPR Familiarity, All Respondents

The majority, 35%, of respondents are familiar with and use GPR through contractors. For agencies in this category, understanding why they contract the work rather than invest in a unit and perform it themselves informs how things such as personal choice, budgetary restrictions, and training limitations create barriers to GPR use. The goal of the curriculum is to make GPR more accessible to Georgia Municipalities, so learning the barriers and concerns of agencies within this familiarity category informs the intermediate needs. The choice of what these needs are and how to address them will be determined through interviews. Once the familiarity of all respondents was determined, this data was further divided by size and budget. Figure 20 shows the percentage of each agency size in each category of familiarity. An unpredicted observation from this data is that the small category is the one with the highest percentage of agencies that own and operate their own units, and the large category has the lowest percentage. The low number of responses influences this, but it is still significant as the small agencies have the smallest average budgets and can be assumed to have less staff than the large agencies. Agencies with lower budgets and fewer personnel being more likely to own and operate their own unit suggests that they have determined a certain advantage that makes GPR worth the money, time, and effort. Based on the inconsistencies mentioned at the beginning of Section 6.2 and the number of large agencies that

report being unfamiliar with GPR and its applications, interviews should assist in understanding if and how the departmental division of labor influenced their answers.

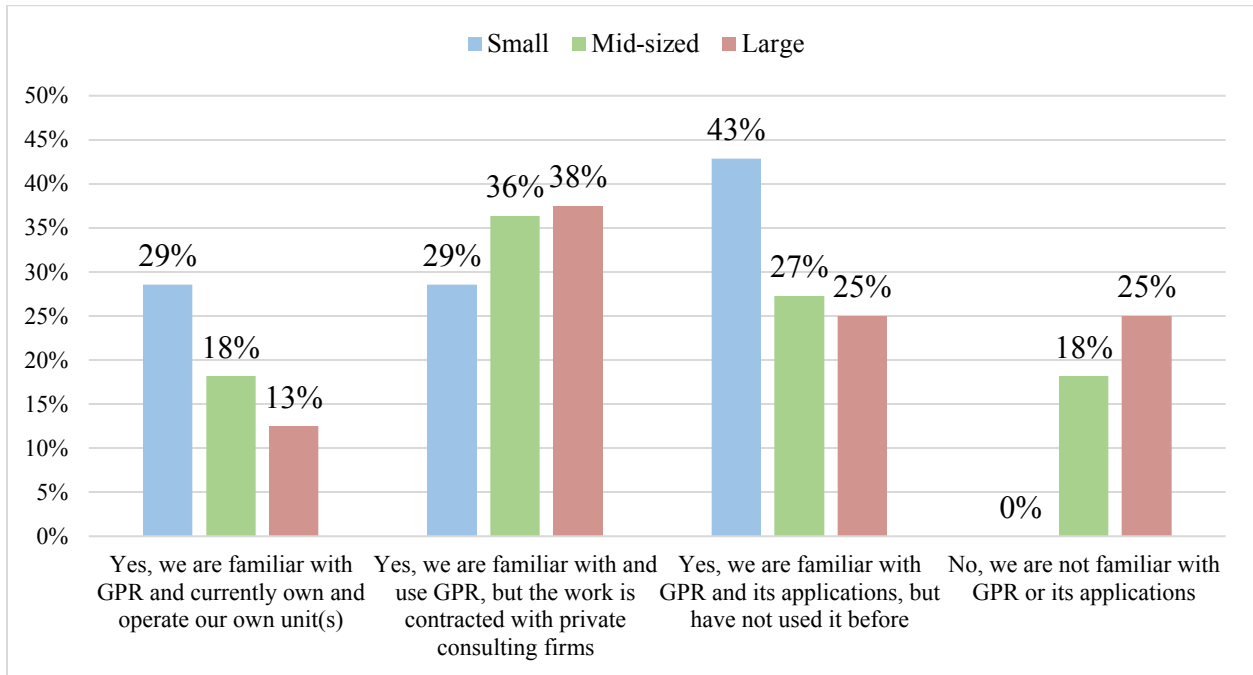


Figure 20: Reported GPR Familiarity by Population Size

Figure 21 shows the average reported general fund budget by size by category of familiarity. When considering the effect that budget has on familiarity using the reported data, it is important to acknowledge that there appear to be multiple instances of respondents providing departmental budgets rather than general fund budgets. This is evident as the reported large agency budgets in millions are \$3, \$8, \$32, \$49, \$60, \$95, and \$399. With this in mind, for small and mid-sized agencies, the highest reported average salary is for those who own a unit, and the lowest is for those who hire contractors. However, the highest average budget for large agencies are those that work with GPR consulting firms. This average is greatly influenced by the city of Atlanta’s budget because there are only three agencies in the category. Overall, the agency budget does not appear to influence its familiarity with GPR.

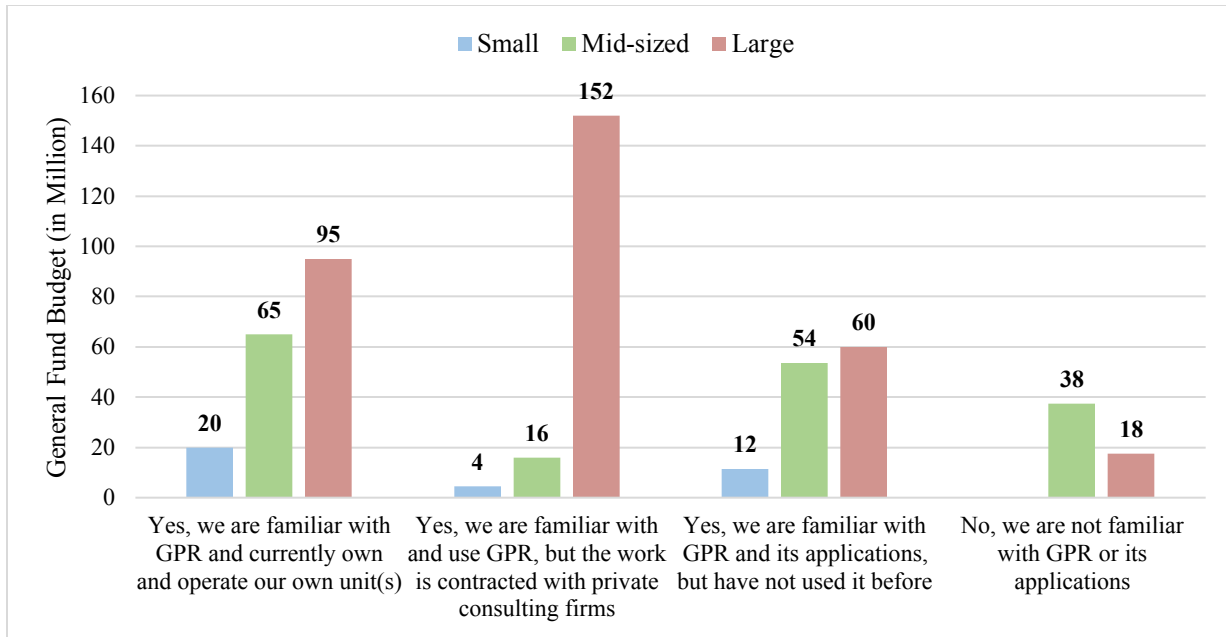


Figure 21: Average General Fund Budget by Size and GPR Familiarity

6.2.2.2 | GPR Interest

The second question polled the respondents’ interest in adopting the use of GPR. The answer choices are “No, we do not see GPR being helpful for our work; We are unsure, but would like to learn more; Yes, we are very interested in adopting the technology; and We have already adopted it.” This question is to help determine which of the agencies that know of GPR but don’t use it are uninterested versus unable to access it as a resource. Figures 22 shows the results of the question when not considering it broken down by agency size. Out of all respondents, only two claimed that they do not see GPR being helpful for their work.

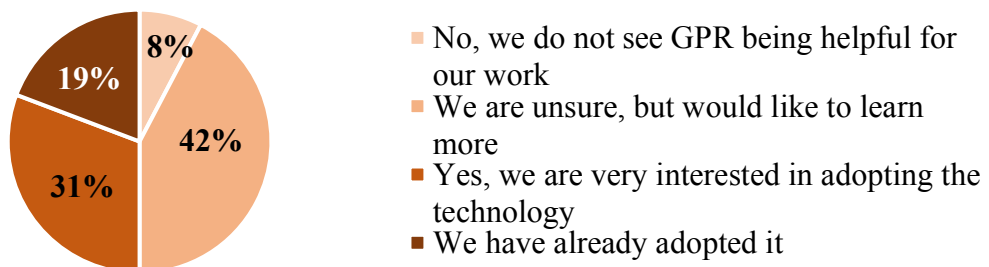


Figure 22: General Interest in Adopting the Use of GPR

Figure 23 shows the results when considering agency size. The disproportionately high percentage of small agencies that have already adopted GPR by owning a unit or working with consultants should be considered a priority in further data collection by interviews. Knowing how and why these agencies with smaller budgets and fewer personnel have chosen to use GPR compared to why others feel it would be unhelpful is a way to outline the proposed decision matrix in the curriculum. In the previous question considering GPR familiarity, 50% of large agencies reported having worked with GPR either in-house or through consultants. This difference suggests a discrepancy in the data compared to the interest question in which only 13% of large agencies report having already adopted the technology. This observation does not disqualify the data, but it should be considered that there is some miscommunication between the question's intention and the respondents' understanding of it. Either way, there is a high rate of interest in adopting and learning more about GPR as a resource. This data suggests that access to educational resources specific to municipal use would lead to a higher rate of GPR implementation.

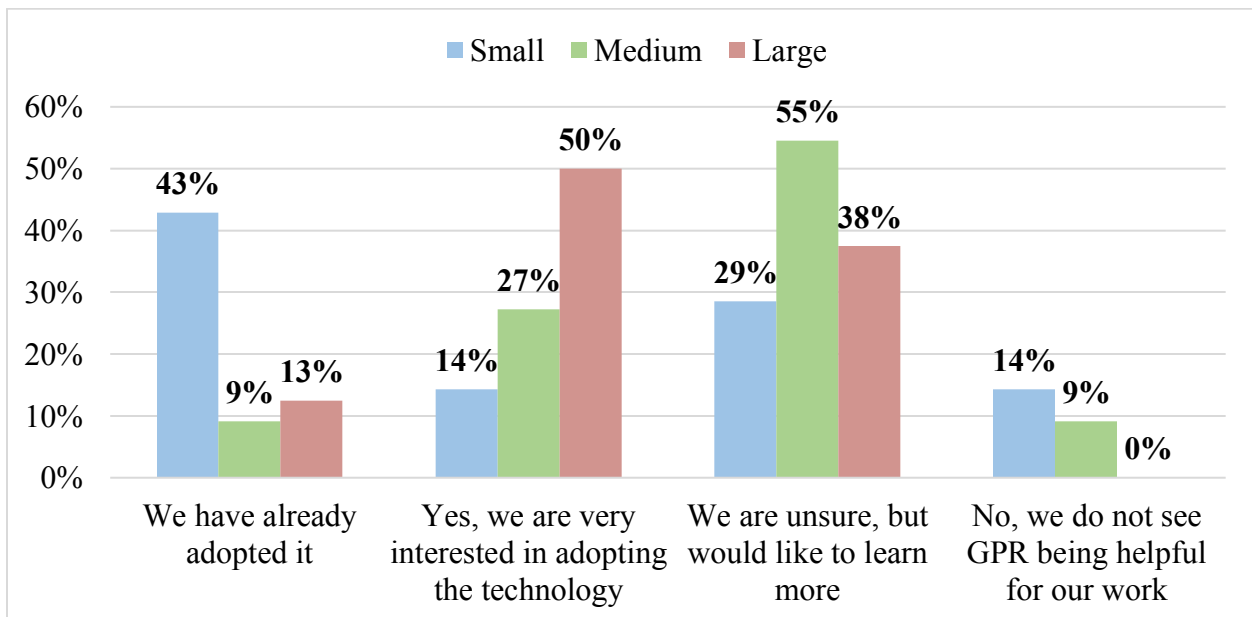


Figure 23: Interest in Adopting the Use of GPR by Size

Following general interest, the third question was to see the respondents' interest in the common uses of GPR identified in the preliminary review. As shown in Figures 24 and 25, the application with the highest interest is locating and mapping utility lines, which knowing how many of the respondents specifically represent their agency's utilities departments, is more in line with their needs than concrete, bridge, and/or dam inspections. To accommodate the respondents' various responsibilities compared to their GPR interests Figure 26 shows the respondents' interest in using GPR for only services they currently perform. According to this data, resources for small agencies should prioritize education on the opportunities available outside of utility locating and how to integrate GPR as a resource within their agency rather than relying on external hiring. Interest in other GPR applications in addition to utility locating may be increased by including resources on how to pool funding and personnel resources from different departments to create a multidisciplinary team. There is a greater overall interest in the use of GPR by mid-sized agencies compared to small, but lack of use for provided services other than utility locating suggests that they too would benefit from educational resources on available applications of GPR. The city of Statesboro represents the 9% of mid-sized agencies that report using GPR for utility locating but did not select utility locating as a provided service in the Agency Services and Budget section. This discrepancy accounts for 0% of "currently use" responses for utility locating by mid-sized agencies in Figure 26. For large agencies, 0% of the responses in Figure 26 are reported as "Not Interested." Reasons for this may include large agencies being better equipped to support GPR use based on budget and staff numbers and providing such services more frequently. Curriculum priorities for large agencies thus far are communicating what makes a GPR survey successful and user training.

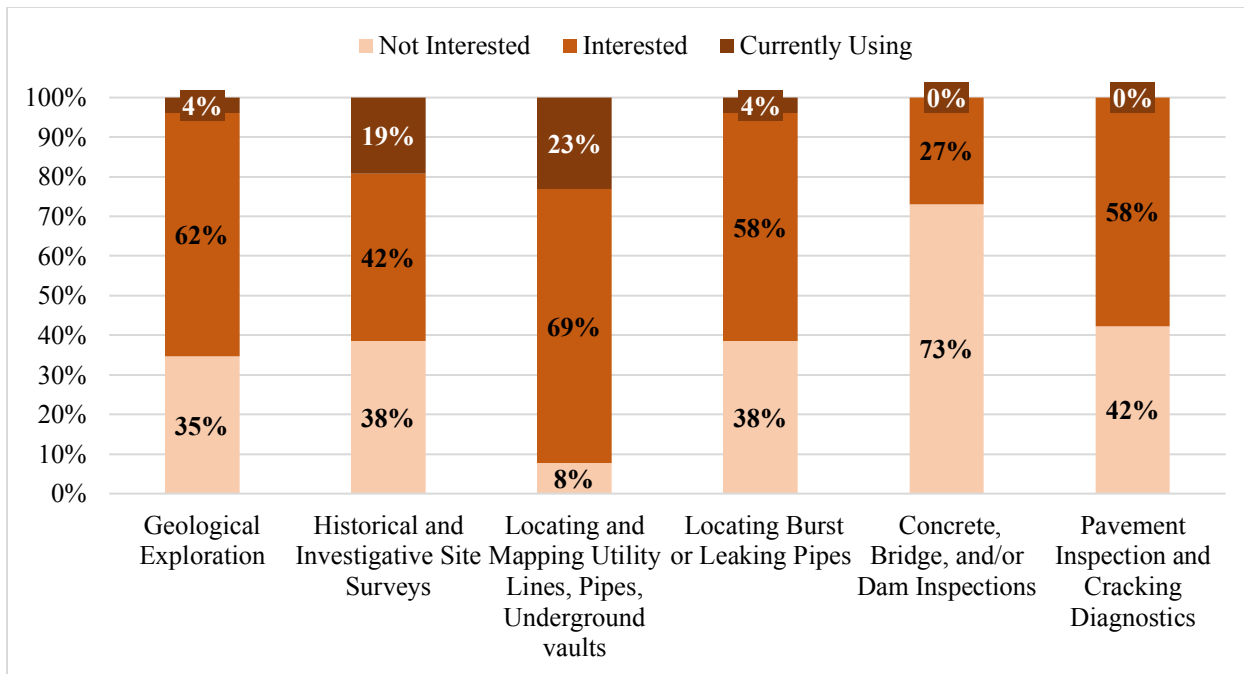


Figure 24: General Interest in Common Applications of GPR

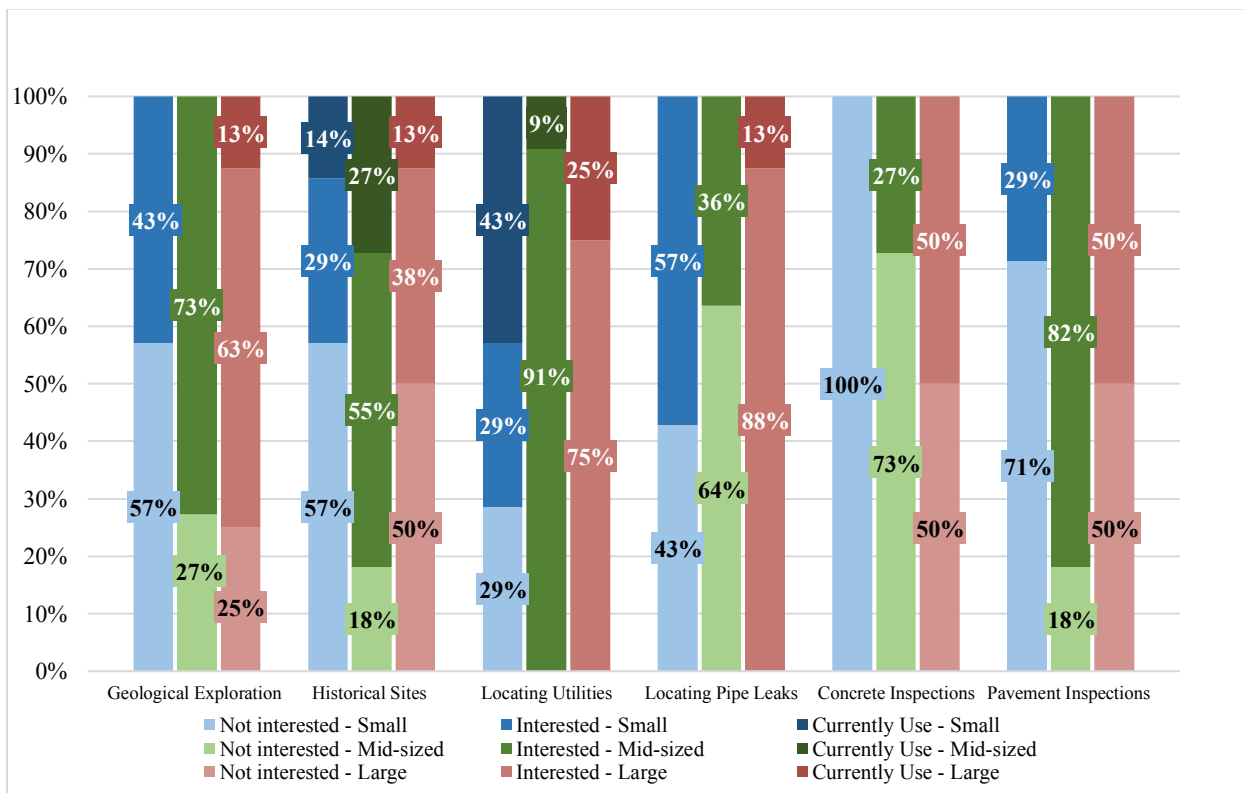


Figure 25: Interest in Common Applications of GPR by Size

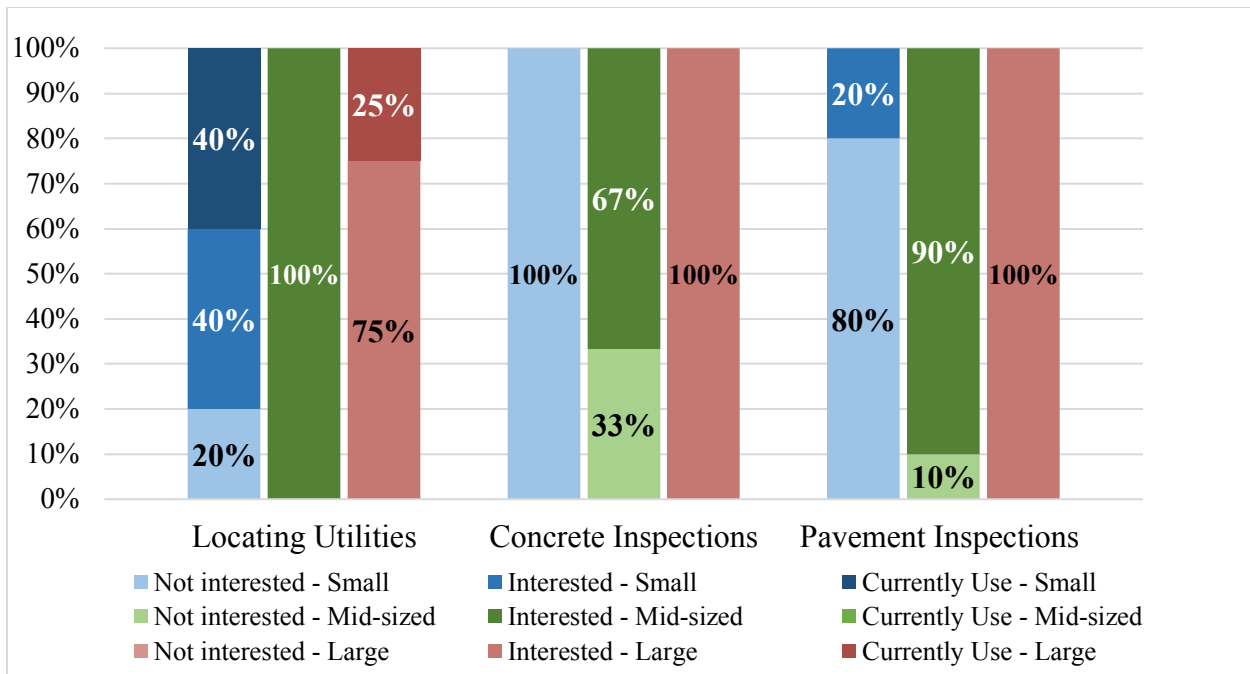


Figure 26: Interest in GPR Use for Services Currently Provided by Respondents

6.2.2.3 | Challenges

The ninth survey question asks respondents to identify what they perceive to be the challenges they would have with adopting GPR. As shown in Figure 27, funding is the most frequently reported challenge for all agencies. This issue applies to both those looking to invest in a unit or hire consultants. The proposed curriculum should include the types of funding that are applicable to this type of investment, as well as comparisons of GPR expense versus cost savings. The curriculum has the potential to serve as a resource for those hoping to convince committees of the cost-effectiveness of such an investment. The second highest-ranked challenge, training and operating, is likely the most difficult to overcome given the constraints of what can be reasonably achieved by this project. For agencies with a high turnover rate, as was reported in the Section 6.3 interview with the city of Atlanta, the challenge of training employees is more than just the learning curve associated with GPR, but also the cost and time required to train new employees to use the technology. This concern can be observed in Figure 28, where the most reported challenge for

large agencies is training and operating at 57% of respondents, followed by funding at 43%. The challenges associated with selecting could be overcome provided a resource that outlines the various capabilities, parameters, and reasonable expectations of GPR use. Once the introductory knowledge needs are met, agencies will be better able to navigate manufacturers' resources and options. In addition, agencies would benefit from knowledge sharing and feedback on how various units have worked for others and what resources are worth the investment. One reason knowledge sharing would be helpful is for challenges associated with environmental factors. The State of Georgia has a diverse landscape, and what will work best in areas such as the Blue Ridge Mountains will not be as applicable to the coastal regions. The low ranking of the environment as a perceived challenge is likely because it requires more than an introductory knowledge of GPR to understand how it is of concern.

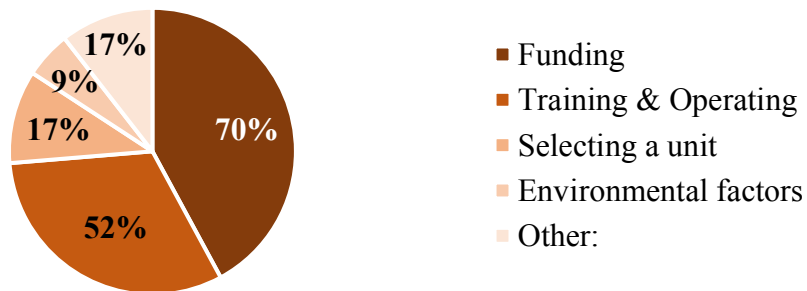


Figure 27: General Perceived Challenges with Adopting the Use of GPR

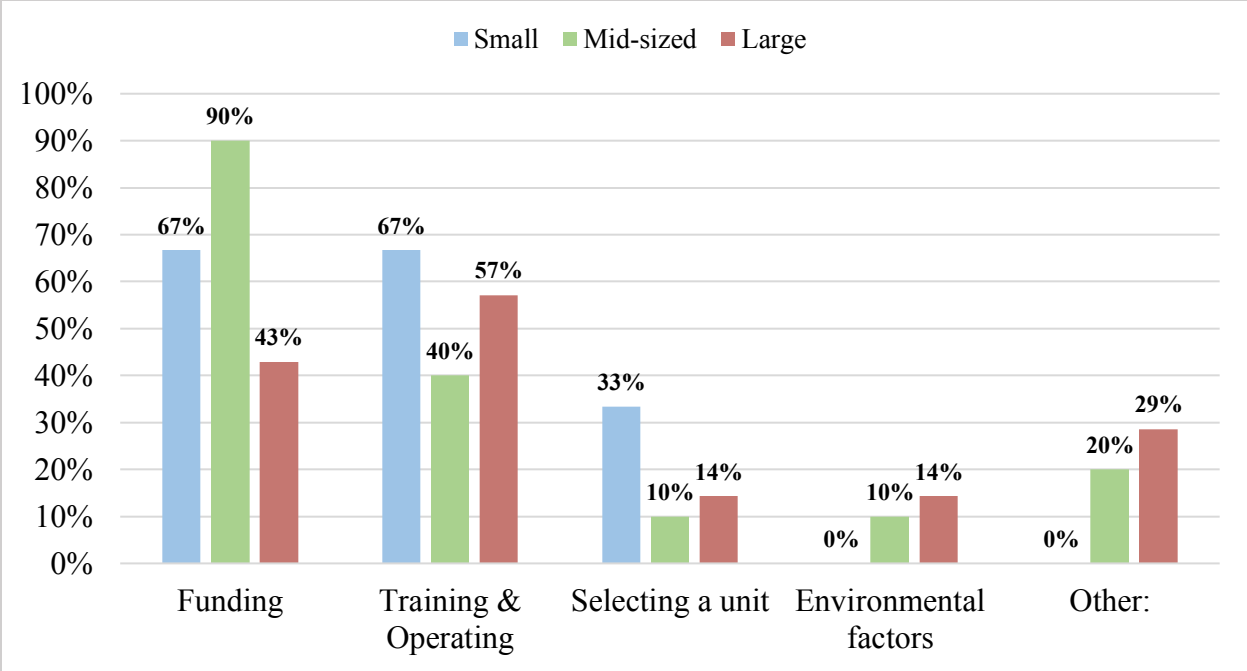


Figure 28: Perceived Challenges with Adopting the Use of GPR by Size

For challenges related to agency size, as shown in Figure 28, the lower rate of the number of challenges large agencies associate with GPR compared with small agencies indicates a knowledge and interest gap between the two. The two large agencies that selected the “Other:” category as a challenge, both listed their lack of knowledge and interest as their reasoning. For agencies that can meet the needs of their communities given their current resources, it makes sense that a technology requiring extensive training would be as less appealing than to an agency with much to gain from the potential time and cost savings. 33% of small agencies reported selecting a unit as a challenge, the highest percentage in the category, can be addressed by meeting the knowledge gap, connecting them to manufacturers willing to give demonstrations, and helping to inform how to select a unit with the ability to meet their specific needs. The implementation of GPR by Georgia APWA agencies is not compulsory, and the intention behind the proposed curriculum is to better inform their choices and understanding surrounding this potentially valuable resource.

6.2.2.4 | Employee Training Methods

The final required question topic for all respondents concerns what they consider to be the most accessible and appropriate method of training their staff to operate GPR. This data is collected by asking them to rank the options “Written guide, In Person Workshop, Online Module, and Other:” in order of most to least preferable. Figures 29 and 30 show each agency's first and second-choice training method. From this data, agencies prefer in-person workshops to either of the remote methods. It would be challenging and not necessarily possible to support repeat in-person training through this project, given the diversity of unit options and the temporary team associated with it. Because of this, a better choice would be to provide educational written and video content that facilitates an agency’s ability to find resources specific to their needs and make the most of the standard, albeit brief, in-person trainings held by manufacturer demonstrators.

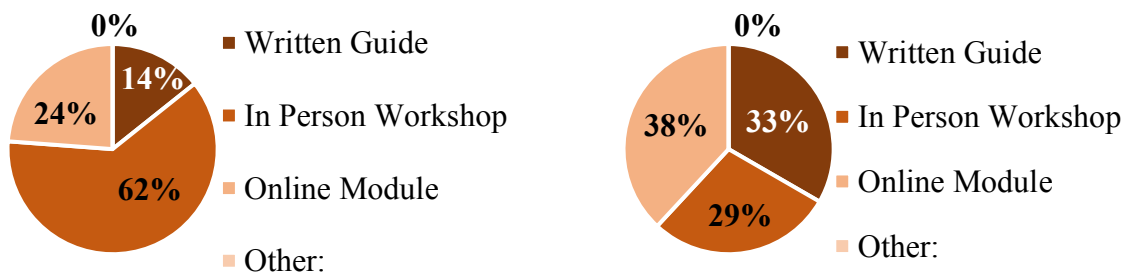


Figure 29: First Choice Training Method **Figure 30:** Second Choice Training Method

6.2.2.5 | Negative Experiences

Four agencies answered the follow-up question asking to describe if they had had any previous negative experiences with GPR. Three of these agencies own their units and listed negative experiences such as difficulty reading the data and locating objects in disturbed or non-flat terrains and the time required for the surveys. Additionally, one agency that has considered but not yet purchased a unit listed their negative experiences as it requires a high level of training and the vendor demonstrations had limited success locating objects.

6.2.3 | Current GPR Users

Access to the final survey section is restricted to current GPR owners and operators. This section is included to learn more about their procurement process and training methods. Only two of the five agencies that report owning a unit completed the questionnaire, so it is a priority to interview each of the five to learn more. The two that provided answers used a manufacturer demonstration by the company Radiodetection to select their unit. Both purchased an RD1100 model and received training through the provided in-person demonstration after purchase.

6.3 | Interview Results

Eight Georgia agencies participated in conversational interviews to enhance the survey data on their experiences. Shown in Figure 31, participants included one small, two medium, and eight large agencies.

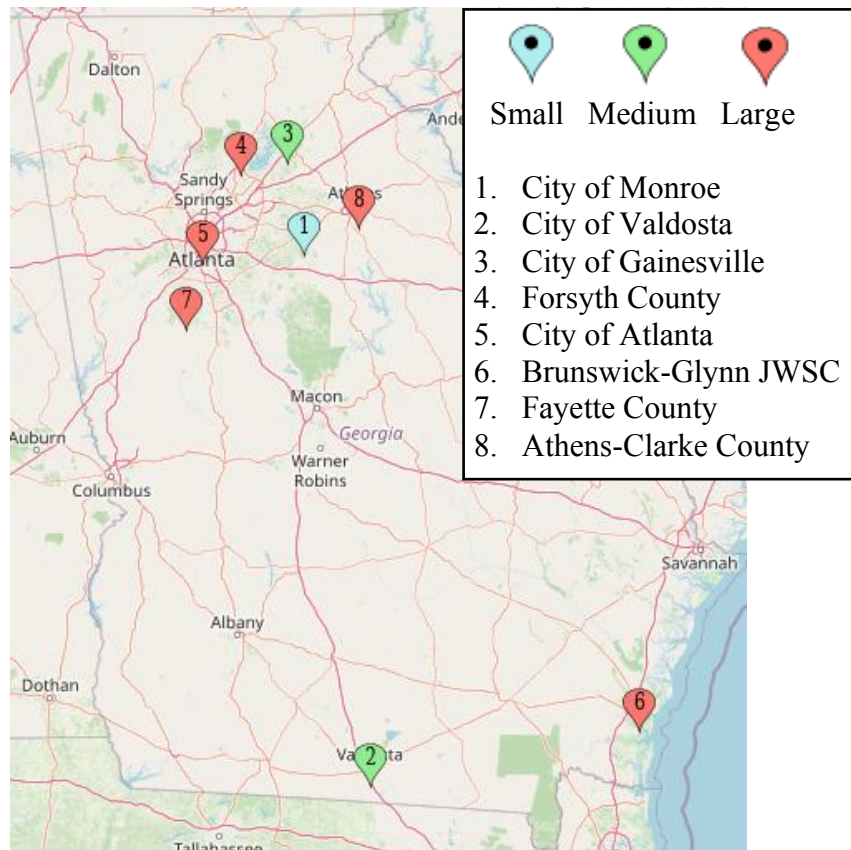


Figure 31: Map of Interview Participants

6.3.1 | Small-Sized Local Government Interviews

6.3.1.1 | The City of Monroe

Ross McMurry is the Damage Prevention Supervisor for the City of Monroe Utility Department. He is responsible for all underground locating and fault finding for the city. The city of Monroe purchased a unit once locating services were brought in-house [conducted within the utility department] and it was determined that it would be beneficial to have the equipment immediately available when needed. The city had never personally hired private contractors before purchasing their unit. Mr. McMurry clarified that in the past they had worked with engineers who owned their units but had never hired anyone for GPR surveying.

The city of Monroe owns a RD1100 unit from Radiodetection. This unit was selected as they use Radiodetection products for their other equipment, and the manufacturer's salesman offered them a demonstration of the unit. Funding for the unit was provided by a combination of the utility department's gas, water, and sewer budgets. Mr. McMurry was unable to provide a price estimate for the unit's initial cost to purchase. Mr. McMurry is the only employee with GPR training and is the sole operator of the unit. There is another technician in the department who is somewhat familiar with the technology but has never received any formal training or used it on their own. Initial training was provided by manufacturer demonstration. Mr. McMurry describes this as the "bare minimum" of the training necessary to operate the unit. He considers that most of his "training" occurred while using the unit. Mr. McMurry says that he did not have the training necessary to identify specific traits of certain utilities before in-the-moment troubleshooting. He claims that most of his practical training came from Radiodetection YouTube videos on how to use the RD1100 unit specifically.

Mr. McMurry reports that the unit was purchased to be used for water and sewer line locating. Water locating remains its primary use as it is now used less frequently on sewer lines. The city of Monroe benefits from using GPR for locating pipes as they have old water lines in their system that do not locate well without it. These lines are likely schedule 40 white PVC pipes, which are now no longer used due to the difficulty of locating them. They also use GPR on sewer lines, though even with it the process remains difficult. Mr. McMurry claims that the unit is not used frequently due to the effect that its 10+ years of use have had on it. He feels that much of this may be resolved by having the unit recalibrated, which is offered by the manufacturer. Mr. McMurry says that they are not interested in upgrading to a new unit at this time. He thinks that his use of GPR would benefit from learning how to add GPS markers inside of the unit and from being able to see the map while the unit is running so that he can immediately identify his utility.

6.3.2 | Mid-Sized Local Government Interviews

6.3.2.1 | The City of Valdosta

Bradley Eyre is the Director of Utilities for the City of Valdosta, among other departments he is also in charge of the locator staff. According to Mr. Eyre, the choice to purchase a unit was based on the needs of the locator staff. The locator staff is a group of employees responsible for locating water and sewer lines through Georgia 811. [“Georgia 811 is a nonprofit corporation dedicated to preventing damage to Georgia’s underground utilities and promoting public safety.”] The need for additional locating resources was highlighted by a recent city-wide installation of cable that frequently required the rapid locating of utilities to proceed. Additional interest in investing in the equipment came from GPR’s potential to prevent damage to infrastructure and cut down on the cost of damage and repairs. Despite a nearly complete GIS mapping of utilities, they needed another tool to locate assets. GPR was identified as particularly helpful for helping them locate old

infrastructure that did not have to adhere to modern standards. This type of infrastructure includes clay pipes and pipes without tracer wire. They also felt that it has the potential to help them with emergency roadway repairs and make utility locating more efficient. Mr. Eyre clarified that the choice to purchase a unit was more about convenience than cost due to the potential benefit of integrating it into the GIS mapping program. Their GIS mapping program covers approximately 400-500 miles of city water and some sewer. Mr. Eyre reported that there have been previous instances where they have needed to hire GPR contractors. He did not elaborate on the exact circumstance, but it does not occur frequently. He claims that most of the times that GPR contractors were used in the area, they were hired by construction firms to protect them from causing potential damage.

Mr. Eyre reports that the City of Valdosta owns and operates a Leica DS2000 utility detection radar with a dual frequency antenna and CT2000 field tablet. He claims they are happy with the equipment and software, particularly its ability to maintain a good traverse over non-smooth areas, its overall ease of use, and its warranty. He was not sure of the exact upgrades selected but knows that their unit is better than the base model but not as nice as what would be purchased by a consultant. Once they determined that it would be a good purchase to invest in a GPR unit and training, they reached out to several manufacturers. Each manufacturer provided a demonstration, and they were the most pleased with the results and software of the Leica model. Funding was secured for the unit by bringing the proposed purchase to the council, which approved and paid for it using the user fees budget. Mr. Eyre did not provide an estimated cost for the purchase, but online resources claim that these units cost approximately \$19,500 to \$22,500.

As intended by the original investment, the unit is operated primarily by the GIS division. The GIS division and locator crews are housed in the city's utility engineering department and

thus are overseen by Mr. Eyre. It is understood that the intention behind these two divisions working together is so that the GIS database is continuously updated with all new location data points. The stormwater division will assist in locates when necessary. Additionally, Mr. Eyre claims that the department of utilities is willing to lend out the team and device to other departments interested in performing surveys. Formal employee training was performed via manufacturer demonstration. He described the demonstration as an extensive one-day event in which a similar model was used in rigorous areas of hard-to-locate utilities. The training was included in the cost of purchase, and similar training was offered by all of the manufacturers they met with. Due to the unit being a recent purchase, less than 60 days before January 11th, 2023, Mr. Eyre reports that they still do not have any formal operation and maintenance or quality control standards in place. He has, however, clarified that employees will have annual training as well as ongoing training whenever the manufacturer has functional upgrades to keep up with the technology.

Mr. Eyre reports that they mostly use their unit for locating and protecting their assets, and roadway work and repairs. It has not become the primary tool for pipe locating, but it remains a valuable asset for the work. Mr. Eyre says that they are “absolutely” satisfied with the process and results citing that GPR is the only way for them to locate forced mains and mains that do not have tracer wire without digging potholes. He says that though it is just another tool to help with mapping, locating, and keeping up with GIS, its improvements to emergency repairs and right-of-way work make it very valuable to them. Mr. Eyre suggests that if other municipalities are thinking about purchasing one, it is worth it and pays for itself within a short period. He did, however, include that while it has been very useful it is not the answer to everything, and it helps if one is looking for a specific thing rather than finding a previously unknown object. Additionally, it takes

skill to read the display and radar images. In his opinion, scans of pipes filled with water or sewage are the most visible, particularly if there is some flow. An empty pipe or gravity pipe is more challenging to locate.

6.3.2.2 | The City of Gainesville

Chris Rotalsky is the Public Works Director for the City of Gainesville. As the director, he oversees the director's office & engineering, traffic engineering, public lands & buildings, Alta Vista Cemetery, vehicle services, solid waste, street maintenance, and Lee Gilmer Memorial Airport. The city of Gainesville currently does not own or operate a GPR unit but has previously worked with consultants. Mr. Rotalsky reports that they do not use GPR [or GPR consultants] on a regular basis and that if they are aware of a problem, it is easier for them to dig up the known issue than run a survey. Additionally, in his opinion, the city of Gainesville's most notable experience of the public works department working with GPR consultants was for a survey of their cemetery. They decided to conduct the survey to determine the locations of what they assumed to be approximately 200 - 300 unmarked graves in the historical portion of their cemetery. The survey identified over 1,100 graves. Mr. Rotalsky says that he highly encourages those in charge of cemeteries to use GPR on their land. Mr. Rotalsky could not provide an estimated cost or funding source for this or other GPR surveys.

Mr. Rotalsky said that they have considered purchasing a unit in the past, but for a long time, the cost was a barrier to entry for them. The cost of the unit, employee training, and the manpower required made it infeasible for them to consider. Though the cost stopped them from purchasing a unit in the past, now that it has come down they are once again looking into their options. Their public works department is responsible for eight divisions, including public land management, an airport, and roadway resurfacing. He suggests that he is interested in GPR to assist

in managing these areas, locating voids in developed areas, determining if an area contains soil or debris, and repairing recurring potholes. He is additionally interested in GPR if locating is brought in-house. Due to Georgia House Bill 1372, the Georgia Utility Facility Protection Act will require local governments to locate traffic control devices and traffic management systems as of January 1, 2024. This requirement has increased the City's interest in GPR for locating due to it being a nondestructive surveying technique and the expense they would otherwise undertake by excavating numerous paved intersections or hiring a locating company.

In addition to the questions outlined in **Appendix C**, Mr. Rotalsky offered suggestions of what he would want to see included in the proposed curriculum. He first discussed how they [public works departments] as a group need information that is practical, applicable, and creative with cost-effectiveness. Second, he expressed that public works departments are not traditionally known as a group that utilizes much technology, and projects like this allow directors to go to [city] managers to prove the potential usefulness and benefit of such products. Lastly, when asked for his thoughts on partnership opportunities he suggested the potential benefit of utilizing intergovernmental agreements for either cost or personnel sharing.

6.3.3 | Large-Sized Local Government Interviews

6.3.3.1 | Forsyth County Department of Water and Sewer

Gary Thurman is the Asset Management Specialist for the Forsyth county department of water and sewer. Mr. Thurman does not manage any employees, and reports to Hari Panthayi, the department's Water Systems Engineer. Forsyth County owns two GPR units, one is operated exclusively by Mr. Thurman and the other is operated by the locating department. The choice to purchase a unit was made because it was considered more cost-effective and convenient than hiring private consultants. When purchasing, it was more economically feasible to pay the initial price of

a unit than a repeat contractor fee. Owning one is considered more convenient because it allows them to work on their own timeline without contractor constraints and removes the chance of errors on behalf of communication difficulties. They had not personally worked with GPR consultants before purchasing their units. However, they had worked with contractors that hired consultants when needing to locate public utility pipes to tie in new lines for developments like neighborhoods.

They currently own two Radiodetection RG1100s, purchased in approximately 2018/2019. These were selected via a company representative demonstration for the department of locators after meeting at a conference. At the time, the basic unit was purchased without upgrades as the GPS tracking options were not accurate enough to meet their needs. Now that they have had them for five years, they are interested in upgrading their units. The initial price to purchase both units was paid using the locator's budget, which is within the overall water & sewer budget. No special funding or grants were used. Their current units, from 2018-2019, cost them approximately \$18,000 each. Employee training was a part of the cost of the unit.

The locator's office operates separately, and for asset management, Mr. Thurman is responsible for the operation and maintenance of one unit. The locator services employees were trained via manufacturer demonstration. The training was done in a one-day event at one of their treatment plants and focused on learning about data output. Mr. Thurman was then trained by the locator manager at a later date. He improved his knowledge through practice and online GPR training on what he was interested in like data interpretation and field techniques. His online were free online tutorials and webinars offered by GPR equipment managers and YouTube. These resources included information not mentioned in previous [secondary] training concerning data interpretation and limitations. Topics include how soil settlement, iron-rich sediment, clay, etc.

can influence the scan. As the primary operator of the unit, he says that there are no formal quality control standards in place, and the reading process is up to his discretion. No maintenance issues or concerns were reported.

The Forsyth County Department of Water & Sewer uses GPR for pipe and asset locating. It is used as a last resort if no adequate GPS coordinates are available or if they receive inconclusive results from using a Pipehorn locator. [Pipehorns are systems that use frequencies to locate conductive materials only.] Uses of GPR mentioned include locating valves buried under objects like roads or bridges during construction. In his experience, this works best for surveying under smooth surfaces but will likely be inconclusive if the box around it is broken. Though it has limitations, GPR's ability to be accurate to the cm can save thousands of dollars by reducing the time and resources spent excavating areas searching for an 8 to 10-inch (203.2 - 254 mm) diameter box. In his experience, he says that his GPR work has a 50% success rate as the imaging and echo limit the visibility and clarity of scans. He attributes some of the error to equipment quality, and other limitations like clayey soils. From his experience, he reports that GPR works better with ductile iron pipes [commonly used for potable water transmission] than polyvinyl chloride (PVC). In terms of depth and size, he says that a 16-inch (406.4 mm) pipe buried 4-5 feet (1.2 - 1.5 m) underground can be picked up more easily than a 4-in (101.6 mm) PVC pipe buried 5 to 6-feet (1.5 - 1.8 m). Primarily his challenges are with crowded areas, clay soil, and rocks that make interpreting data more difficult. He feels that despite his reported 50/50 outcomes, GPR is still a valuable tool for his work that can save time and money by using it instead of methods like potholing.

6.3.3.2 | Fayette County

Matt Bergen is a Project Manager with Fayette County Environmental Management. He previously worked with the water services department, which owns three GPR units. His current responsibilities span from utility coordination to the project management of vertical projects. Fayette County owns and operates three GPR units, the first purchased in 2008, the second in 2018, and the third in 2022. The first GPR unit was bought to meet their need for equipment capable of identifying non-conductive utility pipes. Previous damage due to mismarked utilities included a drill hitting a water main and washing out two sections of roadway that cost approximately \$88,000 and \$100,000+, respectively, to repair. The high price of these damages made the price to invest in a GPR unit extremely cost-effective by their standards. Mr. Bergen reports that Fayette county had not worked with GPR contractors before purchase but did consult with one while selecting their units.

Fayette County owns and operates a 250MHz MALÅ unit, a 250MHz US Radar unit, and a 400 & 800 MHz dual-antenna Impulse Radar PinPointR unit. The MALÅ unit was purchased in 2008 and was selected through the previously mentioned consultation and manufacturer demonstrations. The 250 MHz antenna was selected as they needed it to be strong enough to read 6-8ft (1.8 - 2.4 m) in rocky soils. Mr. Bergen reports that two of the demonstrations, performed by what he considers to be “good, name brands” were unsuccessful, but the MALÅ unit survey showed the curvature of the main, making it their preferred choice. The following units were selected via manufacturer demonstration. The decision not to purchase a second MALÅ unit was due to software issues they had experienced with the original. However, Mr. Bergen clarified that he feels these issues were not due to the manufacturer but rather the age of the 2008 equipment compared to the newer, clearer technology available in 2018. The units were purchased using the

County's enterprise fund for water services, and the purchases were justified by their need for technology capable of locating plastic pipes. According to Mr. Bergen, the 250MHz MALÅ cost approximately \$18,000 in 2008, the 250 MHz US Radar \$26,000 in 2018, and the PinPointR kit for \$22,750 in 2022. The PinPointR kit consists of the GPR unit with tablet for \$16,250, a transport case for \$1,500, and a GPS survey kit for approximately \$5,000.

Employee training was included in the cost of the units, and each involved an in-person representative workshop. He claims that the MALÅ training took place over two days, the US Radar training lasted a week, and the PinPointR training had one day for the GPR and a second day for the GPS kit. No other external training occurred. Further knowledge came through time and experience. To Mr. Bergen, the most important aspect of training is learning how to use the unit's adjustments to account for differences in soil type throughout the county and ground saturation. The county does not follow specific quality control standards, and instead refers to manufacturer recommendations. Battery replacement is the only reported maintenance performed on the units.

Fayette county uses its GPR units primarily for utility marking, including during construction planning. In the planning stages, GPR assists in determining water line placement to avoid conflict with mains. Cost-savings can also be realized by knowing when the site cannot be designed around the current mains early in the process so that they are relocated before rather than during construction. Additionally, GPR improves their SUE quality level from D to C. Mr. Bergen feels that they are absolutely satisfied with their GPR results, and reports that scans are successful 95% of the time. In his experience, as long as the unit is adjusted and "dialed in" the survey will accurately identify objects and their depths. He considers saturation to be the primary cause of the

5% of unsuccessful scans. In Mr. Bergen's opinion, there have been fewer than five damages due to mismarks since they began using GPR.

He offered two pieces of advice to those considering purchasing a unit. The first is to only take manufacturer demonstrators to sites where you have already dug up and identified exactly where the objects and/or pipes are. Doing so, even when instructed to use "random locations," will remove the variable of not knowing from your impression of the survey's success. His other advice is that to really understand how a unit works, you have to run it for about six months to get comfortable with soil and moisture adjustments and it can take an operator over two years to become proficient with it.

6.3.3.3 | The City of Atlanta Department of Transportation

Adisa Aarons is a Field Engineer at the Atlanta Department of Transportation (ATLDOT). Mr. Aarons completed the survey based on his experience with the Department of Transportation and his perceived understanding of the City of Atlanta as a whole. He knows that ATLDOT does not own a GPR unit. He is under the impression that the City of Atlanta is not doing any GPR work internally, as they recently hired an outside contractor to conduct a pavement analysis survey. Mr. Aarons is not aware of more than one previous project involving private GPR contractors. This project concerned the survey of a portion of pavement to study questionable void areas within it. In this scenario, GPR replaced the typical testing method of borehole testing. Mr. Aarons is not aware of the cost of this study but knows that it was funded using the City's general fund budget.

Mr. Aarons claims that the City of Atlanta has not purchased a GPR unit for the following reasons. The first is the liability risk of in-house surveys. He states that it is preferred by the City to incur the contractor cost in exchange for them being held responsible for any concerns of legal liability. The second is the City's employee turnover rate. He suggests that the money and time

spent on the special equipment training for new employees make investing in a unit not cost-effective.

Mr. Aarons's opinion of what the City would be interested in utilizing GPR for appears to be limited to potential uses by ATLDOT. These include pavement assessments and bridge inspections. He listed the use of GPR to replace coring and borehole tests as their primary interest. He did not elaborate on the City's interest in GPR for other tasks.

Due to the limited data and perspective offered in this interview, it may be prudent to seek out a second source to interview for more comprehensive data for the City of Atlanta.

6.3.3.4 | Brunswick-Glynn County Joint Water and Sewer Commission

Todd Kline is the Director of the Engineering, Planning & Construction Division for the Brunswick-Glynn County Joint Water and Sewer Commission. Areas within the division he controls include GIS, Planning & Development, and Utility Inspection. Currently, their use of GPR is through SUE [Subsurface Utility Engineering] consultants. They consider the use of GPR consultants to have become more common as the SUE process is required on more engineering contracts. They themselves do not have experience contracting consultants for GPR work but have worked with engineering firms that have hired consultants. Mr. Kline reports that in 2019 there was a GPR consultant hired by their IT department during fiber cable installation, but the project ultimately decided to locate utilities by open trenching rather than GPR. Additionally, the department reports having sent out an RFP [Request for Proposal] from GPR consultants for a project, but they never heard back and thus did not hire anyone. As they do not have experience hiring consultants, they could not offer an estimated cost or funding for such projects.

Their agency has considered purchasing a unit but ultimately did not. They had the necessary funding and were very interested in investing in one but were dissuaded by the

manufacturer demonstrations. Mr. Kline and his associates report that none of the demonstrators were successful in locating their utilities live, and did not send them any post-processed data or images. They are very interested in the technology and feel that equipment that can prevent damage quickly pays for itself. Given improved confidence and the proper equipment, they claim that they would use it multiple times per week, especially to help locators verify what they are marking.

In addition to the questions outlined in **Appendix C**, Mr. Kline and his associates gave suggestions for what they want to have in the proposed curriculum. First, they would like to know what is necessary to get results in real-time so that they can identify objects while still on site, particularly in emergencies. Second, they would like it to have material describing realistic expectations of what it can do and how to train employees. Lastly, they would like to learn about and have access to external support.

6.3.3.5 | Athens-Clarke County Unified Government

Rani Katreeb is the Assistant Director of Transportation Public Works for the Athens-Clarke County Unified Government (ACC). His department covers capital improvement and roadway projects, bridge and pipe improvement or replacement, minor design work, and creating road improvement priority agendas to bring before officials for approval. Derick Mason is the Engineering Administrator for pavement construction management and design for the Engineering Division of ACC Transportation & Public Works. His responsibilities include managing minor internal design work, project management for capital improvements from design through warranty, pavement management, putting work out to bid, and putting together priority lists and agendas. Jason Mize is the Pavement Coordinator for the ACC Transportation & Public Works Engineering Division. His responsibilities include the development and completion of pavement programs.

ACC does not operate a GPR unit in-house, so their experience with the technology comes from working with contractors. They [Mr. Katreeb, Mr. Mason, and Mr. Mize] report two previous applications of GPR. The first was a project with researchers from the University of Georgia to scan the Baxter Street pavement between Lumpkin and Alps Road. The project identified that the section with the most issues, i.e., recurring potholes and damage, lacks proper soil density and graded aggregate base (GAB). This conclusion determined that the only way to fix the recurring issues would be a full-depth reclamation of the pavement section. When analyzed, the repair and road closure was not cost-effective compared to the price of periodic repairs of the existing roadway. [Chapter 2 includes more information on this study.]

The second application was a scan of pavement subgrade after damage to a water main caused it to burst. The break occurred approximately 10 feet below the ground surface, and the water pressure caused the GPB [did not define] and asphalt to rise. GPR was used to identify pavement bridging and provide information on potential voids in the asphalt. The GPR scan identified which voids were filled properly and the extent of the damage below the ground. The scan data was confirmed using boreholes. The consultants used a GSSI SIR-4000 GPR device with an external 350 MHz Hyper-Stack antenna, and the survey had a penetration depth near 8 feet. [GSSI advertises this unit as having a 0-40 ft depth range]. Due to the nature of the agencies and companies involved, GPR served as a vital documentation tool for step-by-step accountability measures. It saved them money by proving that the GDOT-controlled roadway in the area could be retained, determining the extent of the necessary repairs, and controlling the project cost and work estimations. It can be assumed that paying closer attention and confirming documented utility locations before drilling could have saved nearly half a million dollars in damage. Conducting the

GPR survey and confirming its results using pavement coring and compaction testing cost approximately \$5,000. On its own, the cost of hiring the GPR consultants was \$1,500.

Mr. Katreeb thinks that GPR is essential to use as a county, but not to own. For them, the time and expense of hiring and training a full-time employee to the point of proficiency are not cost-effective compared to how frequently they would use GPR. He estimates that roadway scanning would only take place about every four years. Because of this, the transportation department would prefer to acquire GPR through third-party contractors. Due to the liability associated with roadway work, their council of elected officials favors third-party contractors over in-house scanning. The expertise and knowledge of the staff are considered less reliable than external consultants. Having an external group responsible for the accuracy helps protect them from lawsuits. To them, it would make more sense to hire specialized geotechnical GPR consultants for work related to the transportation department. According to them, since the utility department performs water and sewer pipe locating in-house, they would have more use for it and are more likely to purchase a unit than repeatedly hire contractors. GPR would be useful for completing 811 tickets, as they cannot excavate based on tracer wire locating that does not provide depth information. Despite it being easier to work with the utilities and transportation departments as a unified government, it would be difficult for them to share a GPR unit or employee for survey work.

The following applications are what they consider to be the issues or concerns specific to ACC or similar municipalities that GPR could address. To them, GPR would help with capital improvements and deciding the lifecycle needs of roadways. GPR could be used to determine pavement layer thicknesses and map the best locations for boreholes. Additionally, using GPR to locate utilities and identify that need to be replaced would allow them to coordinate that work with

road repairs and repaving. Combining these efforts would save them time and duplicate expenses. Another feature that GPR could improve is the management of its stormwater infrastructure. ACC manages and maintains culverts and could use GPR in structural inspections of them. In their experience, in 50-60-year-old “small” municipalities, the non-State roadways were not engineered when installed over previously dirt roads. The lack of design leads to pavement failures due to following old standards that lack proper regulation measures. In ACC, this is evident in the difference between the roadway quality on the University of Georgia Campus, whose roads were engineered by the state, and the non-state roads throughout the rest of the county. Another concern with poorly engineered rural roads like these is the effect of increased traffic over time. The rate of wear and tear increases rapidly as they go from minimal to regular or heavy traffic loading. They are interested in applying GPR to identify voids and perform soil density tests at potential construction sites.

In their experience, it is not necessary to be highly technically proficient to understand reports, but having knowledge of the process is beneficial to understand how and why consultants can claim what they’re reporting. The report from their latest GPR project had clear feedback, but some of the voids were not obvious to them and may have been confused for water mains without professional interpretation. Their primary interest is learning how to understand reports and information provided by consultants and how that translates into knowing what work needs to be done. They claim the most valuable tool to help them access and implement GPR would be a GDOT-provided list of approved GPR contractors.

6.3.4 | Interview Summary

Table 5: Summary of Interview Results

Summary Items	Small-Sized	Mid-Sized	Large-Sized
Owners			
<i>Department</i>	Utility department, separate from public works	Utilities department, separate from public works	Water and sewer services, separate from public works
<i>Previous and Current Uses</i>	Water and sewer line locating	Asset locating and protection, pipe locating, improving GIS maps	Pipe and asset locating, improving SUE quality levels
<i>Constraints and Challenges</i>	Limited personnel, very few can operate it, training, time needed for data processing	Training, skill needed to read radar images	Training, time to proficiency, calibrating for saturation and soil type
<i>Opportunities</i>	Partnering with public works	Partnering with public works, cemetery management	Partnering with public works
<i>Funding</i>	General utility department budget	User fees	Water services enterprise fund
Others			
<i>Previous and Current Uses</i>		Cemetery management	Soil evaluation, utility pipe locating, SUE requirements
<i>Constraints and Challenges</i>		Funding, limiting environmental factors	Liability concerns, previous unsuccessful demonstrations, training
<i>Opportunities</i>		More efficient in-house locating to comply with GA HB-1372	Avoiding expensive damage to assets
<i>Interests</i>		Asset locating, locating voids in developed areas, identifying soil and debris, repair of reoccurring potholes	Site surveys, concrete and pavement inspections, utility locating, damaged pipe locating
<i>Funding</i>			General city funds, external contracts

6.4 | 2023 Guide to Ground Penetrating Radar for Local Georgia Agencies

The following sections describe the rationale behind the content of the *2023 Guide to Ground Penetrating Radar for Local Georgia Agencies* which is presented in **Appendix E** and its cover page is presented in Figure 32.

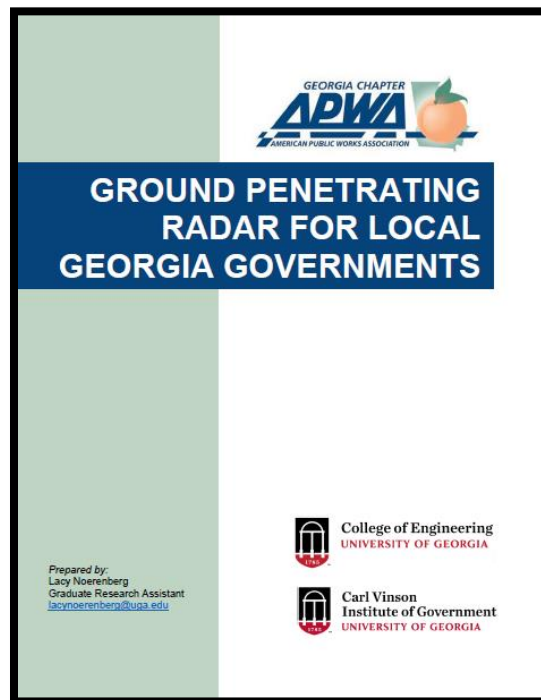


Figure 32: *2023 Guide to Ground Penetrating Radar for Local Georgia Agencies* Cover Page

6.4.1 | Chapter 1: Introduction

The first chapter of the guide provides the purpose and justification of the curriculum, an introduction to GPR, and how GPR applies to asset management.

6.4.1.1 | Purpose

The guide begins with a summary of the purpose of the curriculum. This section introduces how GPR can assist municipal governments with asset management as a non-invasive surveying technique. It then explains the goal of the guide, which is to educate interested Georgia municipalities on how to access GPR and implement it into their work. Lastly, it outlines the three

primary purposes of the guide, which are educating readers on GPR technology, offering guidance for selecting and implementing the technology, and serving as a GPR resource regardless of an end-user's knowledge.

6.4.1.2 | Curriculum Justification

The curriculum justification explains the project background and the data behind why it was made. It cites the project researchers, funding, and the initial survey data used to determine Georgia municipalities' interest in and experience with GPR. For user understanding, the agency population size delimitations established by Dickey 2019 are included to inform how the survey data was collected and interpreted. This section includes a graph of the survey data on the interest in GPR by municipality size to show the current trend(s) of GPR use among Georgia agencies by population size.

6.4.1.3 | What is Ground Penetrating Radar?

The third section of chapter 1 provides a brief overview of ground penetrating radar. This section is included to introduce the technology to users who do not know what GPR is, offer additional context to those unfamiliar with it, and clarify the potential scope of the technology to those familiar with its applications. It provides background on GPR and describes its current applications in civil engineering and asset management, like preventative asset monitoring, geotechnical and structural inspections, utility line and vault locating, and informing design choices.

6.4.1.4 | GPR For Asset Management

The last section of chapter 1 discusses four key ways in which GPR can improve the way that time, money, and effort are spent by local governments on asset management. The areas are increased survey efficiency, decreased utility damages, improved preventative maintenance, and improved construction coordination. Unlike GPR resources made for academic or broad use, this section is

included in the guide to show how it applies to and benefits the work of government agencies. The first area, increased survey efficiency, is included to explain how GPR technology can serve a purpose to those responsible for creating and maintaining maps of assets like utility lines and underground vaults. The second area, decreased utility damages, is included to highlight the benefit of GPR use to locate and protect public utilities. Improved utility protection saves agencies from the expense, construction delays, and potential danger of damage due to burst pipes, leaks, or striking hazardous objects like electric power cables. The third area, improved preventative maintenance, is included to explain how GPR is significant to asset management due to its ability to identify potential failures before warning signs are present at the surface of roads, bridges, etc., without requiring invasive testing procedures. The fourth area, improved construction coordination, is included to show that GPR can help agencies better manage their approach to planning and budgeting for construction. This section emphasizes that it helps with inter-departmental coordination efforts as well as independent projects. Lastly, the section includes a figure, shown in Figure 33 with the four areas related to asset management to communicate GPR's potential to users only interested in reading what meets their specific needs.

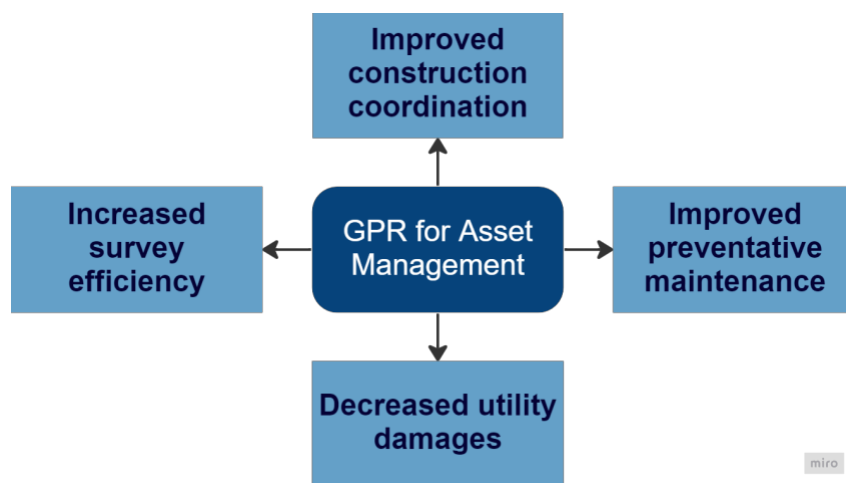


Figure 33: Figure 2 of the *2023 Guide to Ground Penetrating Radar for Local Georgia Agencies*

6.4.2 | Chapter 2: GPR Basics

The second chapter of the curriculum explains the key concepts and information behind how GPR works. By describing how GPR works and the factors that affect its function, the chapter explains how to perform better surveys in addition to background information. The sections within the chapter are “How Does Ground Penetrating Radar Work?”, Antenna Frequency, and Material Properties. These sections were selected based on the key concepts identified throughout the literature review and the experiential feedback from the survey and interviews.

6.4.2.1 | How Does Ground Penetrating Radar Work?

This section is broken down into six subsections. These are “What is a GPR system?”, “How are images created?”, “Why do objects show up as hyperbolas?”, “How can GPR create 3D images?”, “How long will it take to get results?”, and “What influences the success of a GPR survey?”. The purpose of using questions instead of statement titles is to help users align their questions with the concepts behind how GPR works without requiring that they know GPR fundamentals beforehand. An inexperienced reader interested in learning how to interpret radargrams is more likely to identify “How are images created?” as a helpful resource than a title related to, for example, reflector anomalies or generating hyperbolic reflections.

6.4.2.1.1 | *What is a GPR System?*

This subsection is included to describe the components of a GPR system. These include a control unit, an antenna, a power supply, a data storage device, and a distance measurement device. Without this context, readers may assume that GPR is automatically capable of tasks like GPS locating without extra specialized equipment. Additionally, knowing what is necessary for GPR to work helps users better understand the technology and what to look for if shopping for a unit. This subsection includes an image of a block diagram of a GPR electromagnetic pulse to

demonstrate the path of a GPR signal and how the space between the transmitter and receiver will impact the process.

6.4.2.1.2 | *How Are Images Created?*

After discussing the components of a GPR system, the following subsection describes how the technology can image a subsurface. It is necessary to go into detail about how GPR creates output data to explain to readers why the images look the way they do and not, like photographic profiles of the subsurface. The written portion of this section is visualized in a figure of a GPR imaging method. This figure shows the simplified process including what types of things cause the signal to reflect, how one-dimensional images are compiled to create two-dimensional images, and introduces the reason that symmetrical objects like pipes appear as hyperbolas rather than circles.

6.4.2.1.3 | *Why Do Objects Show Up as Hyperbolas?*

A subsection exclusively for describing the cause of hyperbolic images is included to explain the phenomenon and provide further context on how GPR imaging works. Until this point, the signal transmission process is described exclusively as a linear pathway. Though it is helpful to initial understanding, this way of thinking does not explain why two of the point reflections in the figure from the previous subsection have either a longer transmitting wave and a shorter reflected wave or vice versa. The text of this subsection describes the process shown in Figure 34 demonstrating the steps to generating a hyperbolic reflection. Step one shows that the signal has a cone-shaped footprint causing it to register the object before being directly above it. Step two shows two potential signal pathways when the GPR is at location X1. The four following steps go on to show how these reflections measure depth and create a hyperbolic shape. The purpose of including a detailed description of this process is to communicate to the reader the importance of

understanding how much the physical properties of a signal influence the results of a scan. This concept is discussed further in the antenna frequency section.

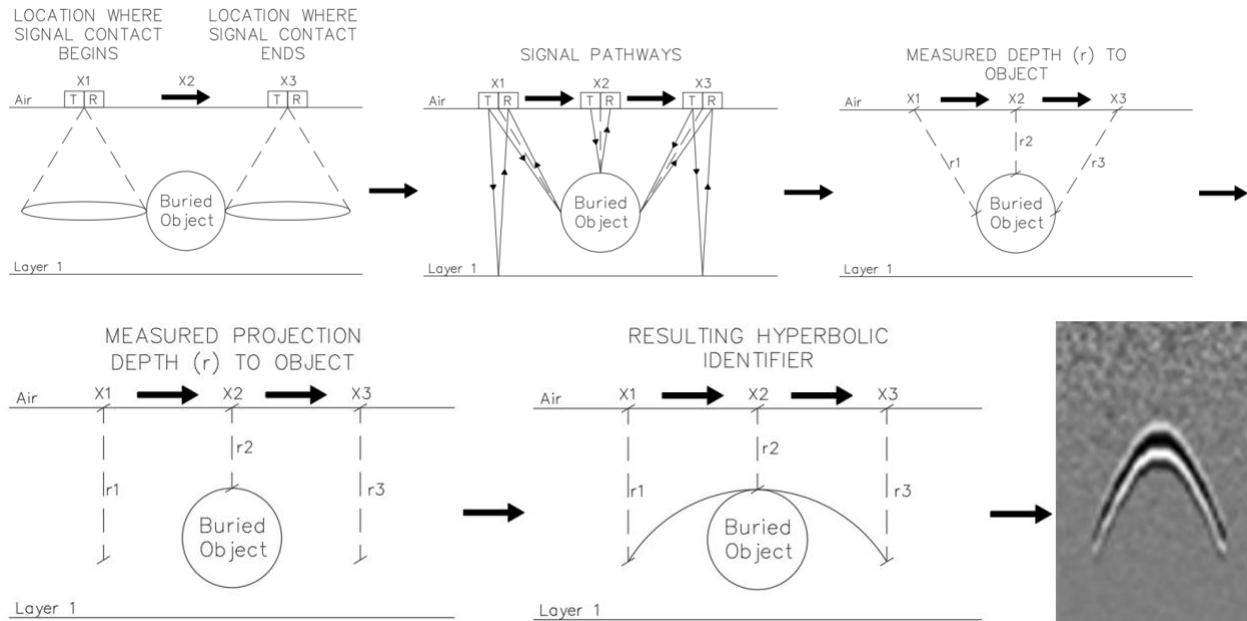


Figure 34: Figure 5 of the 2023 *Guide to Ground Penetrating Radar for Local Georgia Agencies*

6.4.2.1.4 | How Can GPR Create 3D Images?

The introduction of three-dimensional imaging has made GPR even more applicable to underground locating work. This subsection is included to communicate how three-dimensional GPR modeling works in addition to using it to advertise its ability to do so. The process is demonstrated in a figure of a fence diagram with a time slice. Users must understand that the time slice, or horizontal profile data, is not independent or somehow sourced differently from the two-dimensional vertical profile data. Knowing that the horizontal paths shown in a time slice are interpolated from two-dimensional data stresses the need for careful and well-planned data collection. In addition to describing how time slices are developed, this subsection discusses the benefit of scanning in multiple directions. This topic is included because it is beneficial to both new and experienced GPR operators. Experienced users struggling to get high-quality data or interpret it may benefit from starting to scan in a grid pattern rather than in one direction. Lastly,

the subsection clarifies that the system model and software will determine how time slices are formed so that readers are aware that there is no universal way of doing so and that the information in the guide should not be considered comprehensive or complete.

6.4.2.1.5 | *How Long Will It Take to Get the Results?*

The time it takes to get processed data results is extremely important to those interested in implementing GPR. This subsection is included to explain that it is possible to process data in real-time or after the survey but a unit's capabilities will depend on the manufacturer and software used. Due to multiple instances of survey respondents and interviewees discussing the benefit of GPR to right-of-way and emergency repairs, it is clear that the quality of a unit's live data processing is a significant deciding factor for most agencies interested in implementing GPR.

6.4.2.1.6 | *What Influences the Success of a GPR Survey?*

The final subsection of "How Does GPR Work?" is included to discuss the following three sections concerning the factors that influence GPR surveys. These are the material properties of the subsurface, the existence of buried or obscured surfaces, and the antenna frequency used. All of these combined influences how the system must be calibrated for a scan, which is a vital step in training GPR operators. This subsection exists to provide context for, and explain the significance of the following sections. For new users, this will help them learn what to consider before surveying, and for experienced users, this will help them determine if their surveys can be enhanced by improved data collection methods.

6.4.2.2 | *Antenna Frequency*

The type of antenna frequency used is likely the most influential factor in the success of a GPR survey. This section is included in the guide to stress that as the antenna frequency decreases from high to low, the penetration depth increases, but the quality and detail of the image decrease. Many

manufacturers advertise antennas with their penetration depth and do not include the resolution depth. Antenna frequency is an important topic to discuss as the effects of the physical properties of a frequency's wavelength are not intuitive to most GPR users, new or experienced. For agencies interested in deep scans, they need to understand that the low-frequency antennas capable of this will not be of the same quality as high-frequency surveys of shallow areas and it will affect what they are and are not able to locate. Following the introduction to antenna frequencies, the section discusses the application of dual-frequency antennas. This written explanation is supplemented with a figure of a scan performed by a 250 MHz and 700 MHz dual-frequency antenna. This figure is included to demonstrate the difference between the resolution and penetration depth of the two antennas and how they can work together to meet multiple needs at once or be used independently for various applications. The section is concluded using three antenna selection scenarios. These scenarios were developed to provide examples of when to use low, high, and dual-frequency antennas depending on the intended task. Each scenario is based on a GPR application identified to be of interest to local agencies. The low-frequency example is related to surveying cemeteries to locate unmarked graves. The high-frequency example is related to locating concrete reinforcement. The dual-frequency example is related to diagnosing the cause of pavement cracking due to wear or concerns in the subgrade.

6.4.2.3 | Material Properties

This section contains information specifically relevant to performing GPR surveys. It is less relevant to those only interested in learning more about GPR than to those currently or looking to operate a unit. However, it is a way to understand if GPR is useable at an intended site. Understanding the material properties of the subsurface is essential to perform accurate GPR surveys. The importance of learning how to calibrate a scan to reflect accurate properties was

identified to be of significance during the agency interviews. It is a pivotal step to understanding and operating GPR, so it is discussed in detail in the guide. This section is broken down into subsections based on applicable influential properties. These are the relationship between relative dielectric permittivity (RDP) and electrical conductivity, heterogeneity, saturation, and metals.

The relationship between a material’s RDP and conductivity is technically the reason for the way that heterogeneity, saturation, and metals affect GPR surveys. However, these properties have their own sections to provide a more straightforward division of information.

6.4.2.3.1 | Relative Dielectric Permittivity and Electrical Conductivity

The RDP and conductivity of a material are important, yet often overcomplicated, concepts related to GPR. Because of this, this subsection is designed to introduce them as concepts based on how they affect the material properties and signal behavior rather than their technical definitions. To accomplish this goal, the guide includes a written introduction to the topic followed by Table 6 showing the effect of RDP and conductivity on signal properties.

Table 6: Table 1 of the *2023 Guide to Ground Penetrating Radar for Local Georgia Agencies*

Table 1: Effect of RDP and Conductivity on Signal Properties ^[9]			
		Low RDP	High RDP
Low Conductivity	Penetration Depth:	↑	-
	Wavelength Velocity:	↑	↓
	Signal Attenuation:	↓	↓
	Example Material(s):	Dry Sand Granite Bedrock	Lakebeds Freshwater Tables
High Conductivity	Penetration Depth:	-	↓
	Wavelength Velocity:	↑	↓
	Signal Attenuation:	↑	↑
	Examples Material(s):	Gasoline	Saltwater

This table compares the influence that a high versus low RDP has when combined with high versus low conductivity on penetration depth, wavelength velocity, and signal attenuation.

These influences are shown using arrows to indicate an increase or decrease in value. Lastly, the table includes example materials for each of the four categories.

6.4.2.3.2 | *Heterogeneity*

The next material property discussed is heterogeneity. This subsection exists to explain why it is easier to locate an object in a material that shares fewer material properties than one that is similar to it. A figure of a radar signal in a modeled homogeneous and heterogeneous material and a written example are used to communicate this. The figure shows a comparison of a scan taken in homogeneous and heterogeneous mediums. This figure aids in communicating why GPR scans can appear cluttered despite lacking objects. The written example is focused on locating a water table below clay and granite, two materials commonly found in the state of Georgia.

6.4.2.3.3 | *Saturation*

Water content has a significant impact on how a signal travels through a subsurface. The two topics, material saturation and the presence of water in pipes are the primary examples of how this relates to the kind of work done by municipalities. The importance of understanding how rainfall changes a survey's measurements was identified as a crucial topic of consideration in an agency interview as well as in the preliminary review. The difference between pipes with and without water was identified as a helpful suggestion by an experienced agency during their interview. These topics are explained further using a figure of signal attenuation due to saltwater saturation and one of a radargram of an empty steel pipe and a steel pipe with fresh water inside. Each figure helps communicate the difference in scan quality and the extent to which water changes data collection.

6.4.2.3.4 | *Metals*

The metals subsection is included to communicate why metallic objects appear clearly on scans but features below them are obscured and why there are no metallic materials in the example tables. A radargram comparing metallic and plastic objects is included as a figure to show the difference in scan quality and resolution depth between the materials.

6.4.2.4 | Calibration

The final section of chapter 2 is about GPR unit calibration methods. Calibration is identified as a primary factor of GPR survey success in the preliminary review but the processes are difficult to cover comprehensively due to the variation in how different manufacturers approach the process. Because of the inconsistencies in field application, this section instead focuses on why calibration is relevant to the quality of a survey and brief descriptions of common calibration methods. As was identified by the preliminary review, the significance of calibration is that when a GPR survey takes a depth measurement, it records time rather than distance data. Since time is used, it is necessary to know the velocity of the signal through the material to calculate the depth of an object. The calibration methods discussed in the section are estimated table values, known depth to object, and hyperbola fitting. Estimated table values, shown in Table 7, are included because example material property values can be provided in the guide without conflicting with a manufacturer's or software's approach to calibration. Known depth to object calibration is described because the concept is the same no matter the software. Hyperbola fitting is the last and most complicated calibration method included. It is mentioned because it is a common approach, but the guide contains no details concerning the process as it depends on the software and manufacturer.

Table 7: Table 2 of the 2023 *Guide to Ground Penetrating Radar for Local Georgia Agencies*

Table 2: The Approximate RDP, Conductivity, & Signal Velocity of Common Materials			
Ideal Materials for GPR			
Material	Relative Permittivity	Conductivity [mS/m]	Average Velocity [m/ns]
Air	1	0	0.3
Ice	3-4	0.01	0.16
Dry Sand	3-5	0.01	0.15
Granite	4-6	0.01-1	0.13
Less Effective Materials for GPR			
Material	Relative Permittivity	Conductivity [mS/m]	Average Velocity [m/ns]
Saturated Sand	20-30	0.1-1	0.06
Clays	5-40	2-1000	0.06
Freshwater	80-81	0.5	0.033
Seawater	80-81	3000	0.01

6.4.3 | Chapter 3: GPR Applications

The third chapter of the guide describes GPR applications related to services provided by municipalities. These are divided into five sections, geology and hydrology, historical site surveys, locating and mapping utilities, concrete inspections, and roads and pavements. Figure 35 shows the chart at the end of the chapter that is a visual representation of the categories and applications discussed throughout. These applications are a selection of those identified in the preliminary review and those identified as useful by the survey and interviews.

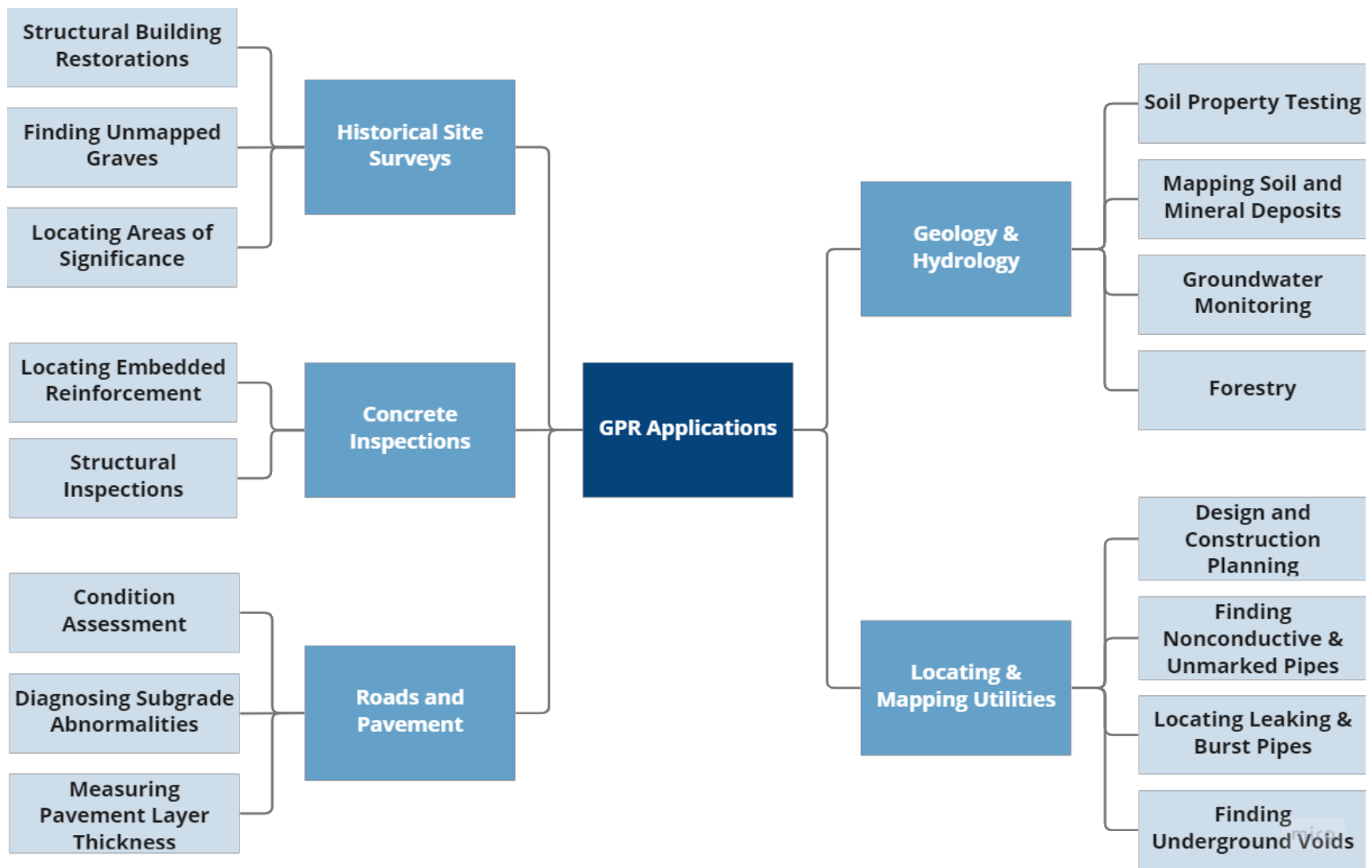


Figure 35: Figure 25 of the 2023 *Guide to Ground Penetrating Radar for Local Georgia Agencies*

6.4.3.1 | Georgia Application Examples

Chapter 3 begins with four examples of how local Georgia agencies use GPR. This section comes before the in-depth explanations of GPR applications because the complicated nature of the technology means that potential uses are not always realistic or of interest to new users. The examples are applications from the interview and survey responses. The first application, non-conductive object locating, refers to GPR uses for locating hard-to-find infrastructure like pipes without tracer wire, clay pipes, and PVC pipes that typically require pothole excavations. The second application, subsurface utility engineering, refers to using GPR to identify the locations and directions of existing utilities to avoid conflicts with them during construction and new utility placement. The third application, more efficient asset mapping, discusses how GPR combined with GPS can rapidly locate and map assets to centimeter accuracy. The fourth application, roadway inspection, refers to using GPR to supplement or replace coring and borehole tests for pavement and bridge deck evaluations.

6.4.3.2 | Expected Outcomes

The second section of Chapter 3 outlines the types of outcomes users can expect from GPR surveys. These outcomes include location, depth, thickness, dimension, orientation, and electrical properties. This section informs users of the potential results of GPR surveys while communicating how they are achieved. Lastly, the section reintroduces the material property limitations like saturation, complete reflectors, and trace intervals discussed in Chapter 2.

6.4.3.3 | Geology & Hydrology

Geological and hydrological applications of GPR related to municipal services include soil exploration, groundwater monitoring, and forestry.

6.4.3.3.1 | *Soil Exploration*

The soil exploration applications described in the guide include mapping soil and mineral deposits and soil properties testing. Though it is a less relevant service, GPR's ability to profile layers of subsurface soils can be used to inspect sites before development and avoid unnecessary destruction of natural features. A figure of a GPR profile showing the discontinuity separating two soil types is included to demonstrate the soil layer profiling that GPR is capable of. The next application is testing soil properties such as water content, bulk density, and stiffness. An example of how this application can be used is shown in the graph of dry density calculated using the GPR versus a sand cone test. In addition to showing an example application, this graph highlights the accuracy of continuous GPR testing compared to point location testing, which allows for more comprehensive asset monitoring.

6.4.3.3.2 | *Groundwater Monitoring*

Groundwater monitoring applications are included for agencies responsible for managing aquifers or those interested in using GPR to locate pipe leaks. The figure showing a 200MHz GPR profile of a low eolian dune with a water table is included as an example of how water tables appear in GPR radargrams. The second figure of GPR scans of two locations before and after a water leak simulation represents the type of data agencies can use to locate where the effects of ground saturation are the strongest to identify where pipes are leaking.

6.4.3.3.3 | *Forestry*

Lastly, a brief description of forestry applications is included to introduce the potential uses. This topic is not identified as having significant interest from municipalities but is included due to the damage tree roots can cause to infrastructure.

6.4.3.4 | Historical and Investigative Site Surveys

The next section, historical and investigative site surveys, is for agencies responsible for historical sites and cemetery management. These applications are included due to the 61% of survey respondents that report being interested in using GPR for historical and investigative site surveys.

The section includes three figures.

6.4.3.4.1 | *Historical Structures*

For historical structures, the figure of a possible interpretation of the roof subsurface between two columns of the Santa Maria del Mar church in Barcelona, Spain, shows how GPR can be used to identify structural elements without design drawings. This application is less common than historical site and cemetery surveys but can be useful to those restoring structures.

6.4.3.4.2 | *Archaeology*

The next two figures are examples of GPR scans for archaeological site surveys. The figure of subsurface anomalies below Santa Maria del Mar is an example of GPR site surveys of a developed area. The figure of the 3D scan of Beechwood Cemetery shows how GPR identifies unmarked graves in cemeteries. This figure and the example from the City of Gainesville cemetery survey are included to show other agencies responsible for cemetery management the potential knowledge there is to gain from a GPR survey of their facility.

6.4.3.5 | Locating and Mapping Utilities, Voids, Storage Tanks, and Underground Vaults

Using GPR to locate utilities is the most popular application of the technology among local agencies. Because most agencies are interested in this application but think it is limited to pipe locating, the section is divided into locating utilities, design and construction planning, and finding voids.

6.4.3.5.1 | *Locating Utilities*

For the subsection on locating utilities, the focus is on the ways that GPR is unique compared to traditional locating devices. These differences include measuring the utility depth and identifying the utility type based on pipe radius. An example of GPR identifying utilities based on object radii is shown in a figure of the detection of four utility types. In the figure, four types of utilities are differentiated and identified based on their radius measured using GPR.

6.4.3.5.2 | *Design and Construction Planning*

The design and construction subsection is related to locating utilities and emphasizes how GPR can save time and money while preventing damage to public and private utilities during excavation. There is no figure for this subsection, but an example experience from the Fayette County interview is included.

6.4.3.5.3 | *Finding Voids*

The final subsection is finding voids. This application is significant to agencies due to the degree to which sinkholes can damage infrastructure. A figure of a void beneath asphalt pavement is included to show how they can form and grow without warning signs of potential failure or sinkholes.

6.4.3.6 | *Concrete Structure Inspections*

The most common uses of GPR on concrete for municipal services are for concrete pavement and structure evaluations. This section is divided into two subsections, locating embedded reinforcement and structural concrete inspections.

6.4.3.6.1 | *Locating Embedded Reinforcement*

Since most GPR scans of concrete pavements are to locate embedded reinforcement, that is the focus of this portion of the guide. Roadways and pavements have a separate section in the guide,

so it would not be an effective use of the user's time to discuss them twice. The figure in this subsection is an example of a radargram and a depth slice of reinforced concrete. The radargram identifies the three longitudinal bars located at the same depth across multiple scans. This figure is included to demonstrate the concepts discussed in the "How can GPR create 3D images?" section and how two-dimensional scans can be interpolated to create depth slices that show the pattern and spacing of reinforcement.

6.4.3.6.2 | *Structural Concrete Inspections*

This subsection is a brief explanation of how GPR can be used in concrete inspections. Additionally, it explains how the scan quality can be lower for thick columns and members with dense steel mesh reinforcement.

6.4.3.7 | Roadway and Pavements

With the development of driven GPR units and automatic data processing, agencies have more interest in their opportunities to implement GPR in their roadway and pavement management.

6.4.3.7.1 | *Pavement Assessments*

This section includes three figures to visualize how GPR can be applied to pavement assessments. The figure of a GPR image of a pavement substructure shows how GPR can identify layer interfaces, reinforcement, and slab joints. The second figure of airport pavement after excessive rainfall and flooding demonstrates how GPR can identify potential failures due to debonding, delamination, and cracking above and below the overlay. These are included as examples as they are common concerns for transportation maintenance departments but require invasive sampling to identify. The third figure of a graph of the density of pavement cracks compared to the depth of reinforcement shows how the depth of reinforcement is correlated to cracking. Scanning to

measure the depth of reinforcement in uncracked sections may help agencies interested in anticipating future pavement damage.

6.4.4 | Chapter 4: Best Practices and Decision Making

The purpose of chapter 4 is to provide communities with the resources necessary to make decisions concerning GPR attributes, funding resources, and training.

6.4.4.1 | Selection of Important Attributes

Most resources on unit type and attribute selection are oriented toward selling a product, not educating users. This motivation can lead to misinformation or exaggerated expectations of a system's capabilities. Additionally, resources for choosing whether to purchase a unit or hire consultants are biased in favor of whoever is attempting to use it to sell their services.

This section includes three subsections. Topics include Own vs. Rent vs. Hire, Types of GPR Units, and Antenna Frequency Selection. Each subsection has a table or decision matrix to supplement the written portion with a quick and unambiguous reference aid. Each table is populated using a combination of the preliminary literature review and agency experience data.

6.4.4.1.1 | *Own vs. Rent vs. Hire*

Though GPR has the potential to benefit almost all agencies' asset management, there is no one way to implement it that is accessible to or necessary for them all. Their differing needs and available resources will influence why and how an agency uses the technology. The three methods of GPR access presented in the guide are owning a unit, renting a unit, and hiring consultants. These options were determined using agency experiences and resources identified in the preliminary review, including manufacturers and independent retailers. Owning and hiring are the more relevant choices to new users, and discussing the option to rent units offers something to

experienced users. GPR operators unable to accomplish an unusual project can consider using rental equipment to meet their temporary needs.

The text portion of this subsection exists to introduce the options of how to access GPR and discuss the common reasons behind user preferences. The introduction is followed by two examples. The first example describes a scenario based on the City of Gainesville's experience hiring consultants to survey their entire cemetery. This example was chosen to demonstrate when to hire consultants because it requires maintaining survey quality for multiple days, the indicators of this type of subsurface objects, and 42% of survey respondents report an interest in using GPR for historical and investigative site surveys. The second example is also from the interview with the City of Gainesville, and it considers how to approach a city-wide survey of traffic control devices. This project was selected as an example of when operating a unit in-house may be preferable to hiring consultants based on cost and necessary GPR proficiency. Furthermore, it is an example of a type of utility locating related to transportation rather than the typical examples of water and sewer pipes. It deviates from the usual example to demonstrate potential inter-departmental benefits of GPR use to those, particularly in transportation departments, that feel it does not apply to them.

The GPR procurement method selection matrix, shown in Table 8, is the conclusion to this subsection.

Table 8: Table 5 of the 2023 *Guide to Ground Penetrating Radar for Local Georgia Agencies*

Table 5: Suggested Method of GPR Procurement ^[2]		
	Own or Rent & Operate	Hire Consultants
Preferences by Department		
Water & Sewer	X	
Utilities	X	
Transportation		X
Departments with a High Rate of Employee Turnover		X
Preferences by Task		
Anything Determining Legal Liability		X
Large Scale Cemetery Survey or Mapping		X
Extensive Locating Projects for Fiber Cable Installations, or Updating Traffic Control Records for GA HB1372	X	
Construction Project Management	X	
Improving the Level of SUE Investigation *	X	X
Determining Properties and Debris Content of Soils		X
Locating Voids in Developed Areas	X	
Daily or Frequent In-House Pipe & Asset Locating	X	
Burst or Leaking Pipe Locating	X	
Utility Locating & Mapping for GIS Documentation	X	
Locating When it is Unclear What May be Found **	X	X
Immediate Response Roadway and Right-of-Way Repairs	X	
Diagnosing Roadway/ Pavement Cracking ***	X	X
Locating Concrete Reinforcement	X	
Locating in or Beneath Densely Reinforced Concrete (e.g., Airport Pavement)		X

* Local agencies that frequently manage projects/ sites benefit from owning & operating a unit

** Well trained and experienced in-house locators may be comfortable doing this, but inexperienced may prefer to hire consultants to either run or interpret the survey

*** Pavement thickness scans are manageable, but understanding the subgrade soil properties may require specialized help

The matrix includes four department-related and fifteen task-related procurement examples. Tasks for which both owning and hiring are suggested are discussed in the comments below the table. The suggested procurement method for each example was chosen based on agency experiences discussed in the interviews and standard practices identified in the preliminary review. The examples for preferences by the department are water & sewer, utilities, transportation, and departments with a high employee turnover rate. Due to the material properties of the objects and frequency of use, it suggests that water & sewer, and utility departments using GPR typically own and operate a unit. Based on the liability concerns identified in the interviews with the City of Atlanta and Athens-Clarke County, the matrix suggests that transportation departments interested in GPR prefer to hire consultants. Overall, no matter the type, due to the time to proficiency and necessary employee training, departments with a high employee turnover rate prefer to use GPR through hiring consultants.

The examples of suggested preference by the task can be divided into five categories. The first is anything determining legal liability. It is necessary to communicate to agencies that legal claims concerning GPR data are complicated and that they need to protect themselves by outsourcing the work. The next category is the tasks in which the survey goal requires a high level of proficiency due to the properties of the target object(s). These tasks are cemetery surveys, soil properties testing, and surveying subsurfaces with unknown contents. Cemetery surveys benefit from consultants due to their quality control measures and experience interpreting radargrams. Using GPR to determine soil properties for design inputs requires precise equipment calibration and potentially multiple antennas, so few in-house operators perform such tasks. In scenarios where there is no data on the subsurface contents, multiple scans should be performed at various frequencies, and a high level of proficiency is required for interpreting the data, making it a task

for consultants. The next category includes construction project management and rapid response right-of-way work. Access to GPR helps prevent avoidable damage in either scenario and operating a unit in-house means there will not be a delay due to the consultant's schedule. Both tasks benefit from having real-time access to GPR and immediate data availability. The next section is pavement and concrete applications. When diagnosing the cause of roadway cracking, moderately proficient users should be able to perform pavement layer thickness scans however determining the cause of cracking due to subgrade soil properties may require specialized help from consultants. Locating concrete reinforcement is a straightforward process due to the agreeable properties of the steel and shallow survey depths between 0 to 3 ft (0.0 - 0.9 m). It becomes a specialized process as the reinforcement density increases and spacing decreases. Due to complete signal reflection off steel, the antenna wavelength must be smaller than the reinforcement spacing. Because of this, these scans require an extremely high antenna frequency that may have too few applications to justify the cost to purchase for municipal use. The final category is the day-to-day locating tasks and long-term locating projects. These can all be performed in-house without extensive training or highly-specific equipment.

6.4.4.1.2 | *Types of GPR Units*

The following GPR attribute subsection concerns the types of GPR units and their suggested applications. It contains two tables, the first a unit type selection matrix, and the second a comparison of the capabilities and prices of the units owned by the agencies that participated in interviews. The purpose of the subsection is to explain how and why handheld, walk-behind, and driven GPR units are utilized for various tasks. Walk-behind units are the most applicable type for tasks related to municipal purposes, but it is still beneficial to provide context as to why. Excluding the other unit types would mean that an agency interested in GPR would need additional

information to understand their options, making the curriculum less comprehensive of a resource than intended. Additionally, it is explicitly mentioned in the text that while handheld units may be used for several other applications, they are excluded for the sake of operator convenience and safety. Handheld units are often more cost-effective than the others but limit how visible the operator is during use, making it unsafe for most applications on or near roadways.

The first table of the subsection is a GPR unit type selection matrix based on standard applications shown in Table 9.

Table 9: Table 3 of the *2023 Guide to Ground Penetrating Radar for Local Georgia Agencies*

Table 3: Selection of GPR Unit Type ^[2]			
	Handheld	Walk-Behind	Vehicle-Mounted
Survey Across Undeveloped Land		X	
Survey of Soil Properties		X	X
Scanning Beneath Developed Areas	X	X	
Locating Utilities Below Ground or Soils		X	
Locating Utilities Below Pavement		X	X
Survey of Structural or Reinforced Concrete Walls, Beams, Columns, and Shallow Floors	X		
Survey of Structural or Reinforced Concrete Floors and Foundations	X	X	
Survey of Pavement Section Properties		X	X
Surveying Pavement and Subgrade at High Speeds			X

The three unit type options are handheld, walk-behind, and vehicle-mounted. These are the only types discussed in the text, so adding the unique or specialized equipment types available would complicate the table and confuse user understanding. The only application listed exclusively for handheld units is the survey of structural or reinforced concrete walls, beams, columns, and shallow floors. Because these elements may be vertical or within enclosed spaces, it is in the user's best interest to only attempt to scan them using a small and easily lifted unit. The suggested

applications for handheld and walk-behind units are scanning beneath developed areas and surveying structural or reinforced floors and foundations. If there is enough space for navigating the unit, outdoor spaces like sidewalks, roadways, patios, etc., can be surveyed using walk-behind units. Handheld units are useful in these scenarios for navigating narrow or hard-to-reach places. Again, if there is enough space to maneuver it, horizontal reinforced concrete elements like floors and foundations can be surveyed using walk-behind units. Handheld units work well for this if there is limited access to or space in the intended area. The suggested applications for walk-behind units only are surveys across undeveloped land and locating utilities below ground or soils. In these applications, the unit must be able to traverse uneven surfaces for an extended distance. It is difficult to maintain survey quality doing this with a small handheld unit, and walk-behind units are more efficient and comfortable for operator use. Walk-behind and driven units are suggested for three applications. These include surveys of soil properties, locating utilities below a pavement, and surveys of pavement section properties. Soil property testing is included in this group because driven units can collect soil data under pavement, but walk-behind units can be used for this or testing unpaved areas. Either method can accomplish the other two applications by traversing the section on foot or by vehicle. Surveying pavement and subgrade at high speeds is the one application included in the table that can only be performed using vehicle-mounted GPR units. Vehicle-mounted units driven at the speed of traffic improve operator safety, remove the need for traffic control measures, and allow for more efficient data collection across large distances.

The second table in this subsection, shown in Table 10, compares the prices and capabilities of five example GPR units. The example units are those currently used by local Georgia agencies to ensure that the table reflects the interests of municipalities and not technical GPR consultants. Unit price and initial attribute information are from the data gathered in the agency interviews.

Information on unit attributes was collected from manufacturer specifications to supplement interview data when necessary.

Table 10: Table 4 of the *2023 Guide to Ground Penetrating Radar for Local Georgia Agencies*

Table 4: Example GPR Unit Pricing ^[2]					
Example Units:	1	2	3	4	5
Antenna Frequency (MHz)	250	250	600	250 & 700	400 & 800
Walk-behind	X	X	X	X	X
GPS Enabled	X	+\$5,000	+\$3,750	+\$1,284	X
CAD/GIS	X		X	X	X
Live Data Processing	X	X	X	X	X
Post Data Processing		X	X	X	X
3D Modeling		In-Post	Real-time	X	
Days of Training Included	One	Two	One	One	-
Price	\$18,000 (2018)	\$18,000 (2008)	\$21,260 (2023)	\$22,500 (2023)	\$15,550 (2023)

Nine potential attributes are used to compare the units. For the first, three units have single-frequency antennas, and two have dual-frequency antennas. Antenna frequency is included in the table to demonstrate that dual-frequency antennas are not associated with higher prices. For the second attribute, all five examples are walk-behind units, as no communities surveyed or interviewed reported owning handheld or driven units. The third attribute considered is GPS. Agencies that report an interest in using GPR to map utilities in land surveys would require systems with GPS integration. Two examples have GPS in the base unit, and three offer it in optional upgrade packages. The fourth attribute is CAD and GIS compatibility. Systems that are compatible with these allow operators to easily transfer GPR data from the device into design and mapping software. The fifth attribute is if the unit processes data results in real time. Real-time results are necessary for agencies interested in using GPR for rapid response work. The sixth attribute is whether the unit allows for post-survey data processing. Post-processing allows for an in-depth

analysis of data off-site to get more sophisticated results. It is a helpful tool for those using GPR data in design and construction planning. The seventh attribute is the ability to model data in three dimensions. Three-dimensional modeling is vital for those using GPR to survey pipe pathways and differentiate between continuous infrastructure and sporadic objects like rocks. The eighth attribute is the number of days of in-person training included with the unit purchase. In-person training is a considerable expense, and agencies looking to make the most out of their initial investment should consider the quality of training provided with purchase. The ninth attribute is the price of the unit. All pricing information is sourced from interview responses and includes the year of purchase for context. Retailer or up-to-date pricing data is not included as it is not available online, and none of the manufacturers responded to inquiries when contacted. The lack of price information available is an example of the degree of knowledge and effort required to begin researching potential options for GPR implementation. This attribute is included so that communities unfamiliar with GPR and its costs will immediately know if the equipment is affordable.

6.4.4.1.3 | *Antenna Frequency Selection*

Proper antenna frequency selection is necessary to perform an effective survey. The differences in penetration and resolution depth depending on the frequency mean that users need to know what they intend to use GPR for before investing in a unit. The type of antenna required for their work will influence which units to consider and whether or not a dual-frequency antenna is necessary to achieve their goals. The guide includes an antenna frequency selection matrix, shown in Figure 11, to help prepare users to make this decision. The matrix compares the approximate depth range of eight frequencies and their corresponding potential applications.

Table 11: Table 6 of the 2023 *Guide to Ground Penetrating Radar for Local Georgia Agencies*

Table 6: GPR Antenna Frequency Applications ^{[2][9][10][43]}								
Antenna Frequency (MHz)	2600	1600	1000	900	400	270	200	100
Approximate Depth Range	(0 – 1 ft)	(0 – 1.5ft)	(0 – 2 ft)	(0 – 3 ft)	(0 – 12ft)	(0 – 18ft)	(0 – 30ft)	(0 – 90ft)
Concrete Quality Control	X	X	X	X				
Structural Engineering	X	X	X	X				
Roadbed Subbase and Layer Analysis	X	X	X	X				
Forestry	X	X	X					
Archaeology				X	X	X	X	
Locating Utilities, Voids, and Storage Tanks				X	X	X	X	
Geology					X	X	X	X
Soil Exploration						X	X	X
Geotechnical Engineering						X	X	X

The applications and frequencies included are based on the work of Bigman 2018 and Stryk et al. 2015. The nine potential applications are concrete quality control, structural engineering, roadbed subbase and layer analysis, forestry, archaeology, geology, soil exploration, geotechnical engineering, and locating utilities, voids, and storage tanks.

6.4.4.2 | Funding

An initial objective of this project was to identify special funding opportunities for communities interested in GPR but unable to afford it, but none were found. The guide must include a disclaimer concerning this, as it was a common request and topic of interest among survey and interview participants. Since there are no funding opportunities to discuss, the funding section emphasizes that GPR is a cost-effective tool and discusses potential interdepartmental funding opportunities. If the section were to be removed due to the lack of data, agencies interested in finding such information would consider the guide incomplete.

6.4.4.3 | Training

42% of survey respondents report training and operating as a perceived challenge with adopting the use of GPR. The introduction to this section begins with a reminder to readers that training is an ongoing process and proficiency will take time. The practice necessary to become confident with GPR technology requires a dedicated effort and means that for agencies with a high rate of employee turnover, GPR may not be a productive resource. Though the goal of the guide is to increase and improve the use of the technology, it is important that it not overestimate the agencies' capabilities. Additionally, the introduction discusses how updated software decreases the time to proficiency. Agencies that have considered implementing GPR in the past but decided against it may be encouraged to try again knowing that the user experience has been prioritized and improved. The section includes three ways to access training. The first choice is through a

manufacturer or GPR retailer. As discussed in Section 6.4.4.1.2, initial equipment training is included with the purchase of the unit via manufacturer demonstration. This is included as a resource for users that assume there is an additional fee for training following the purchase of a unit. The second choice is online resources including free YouTube tutorials and remote certification courses. These are the most accessible training tools for active GPR operators to seek advice through. In interviews with agencies currently utilizing GPR, free online resources are the most common method of operator training and continuing education. Additionally, the section suggests communicating with surrounding agencies to help collect and access material property data. Georgia municipalities have to be adaptable to inconsistencies in their environments due to the state's diverse geological landscape. The third choice is in-person training through GPR consultants. This is included for agencies interested in or needing resources to improve their surveys. It is disclosed in the section that most in-person training workshops require a minimum number of participants that small agencies may not be able to fill or afford. Following this, it suggests that users coordinate with other neighboring agencies to share the expense and develop relationships with other GPR operators.

6.4.5 | Chapter 5: Getting Started

The fifth chapter of the guide is designed to aid communities in their efforts to implement GPR in their work. The process is designated into five steps that are to evaluate needs, select a unit, secure funding, train operators, and implement the technology. This chapter is included in the guide to gather the rest of the guide's information and turn it into an approachable guided procedure.

6.4.5.1 | Step 1: Evaluate Needs

The first step of implementing GPR is determining whether or not it is necessary or possible to use it for the intended task. Pursuing the use of GPR that is unnecessary or unusable for the project is

an inefficient use of agency time, resources, and efforts. This section includes four sets of guiding questions for users to ask themselves to evaluate the use of GPR for a project. They are the following: “Does it make sense to use GPR?”, “What are the project goals?”, “Will GPR work at the site and for the project?” and “Is in-house or hiring consultants better?”.

6.4.5.1.1 | Does It Make Sense to Use GPR

The first guiding question asks the user to consider if GPR is capable of solving a problem that current equipment either cannot do or does less efficiently. Although GPR is a versatile tool with significant cost and effort savings potential, it is not guaranteed to be a necessary or useful asset. Agencies should consider if it is worth the time and training before investing.

6.4.5.1.2 | What Are the Project Goals?

The intention behind a project should be considered to evaluate the potential benefits or disadvantages of implementing GPR. The first guiding question asks the user to consider what the survey is looking for. In scenarios where there is a known object in an area, it will be easier to find and classify than if the scan is of a subsurface with no predictable contents or an undeveloped area. The potential of the scan will depend on operator experience, and new users should have reasonable expectations of what they will be able to identify. The second asks the user to consider if the GPR results can be confirmed using alternative testing methods. Using additional alternative testing methods improves the quality of the GPR calibration and supports the findings of the non-localized results.

6.4.5.1.3 | Will GPR Work at the Site and For the Project?

Site constraints and terrain will determine if a GPR survey can be performed at an intended location. The first guiding question concerning site feasibility asks the user to consider if the site is clear of obstructions that would limit the maneuverability of a unit. Interview data from agencies

implementing GPR shows that municipal operators are more comfortable and capable of scanning smooth surfaces than rough terrain. Additionally, if there is dense ground cover in the area the operator will not be able to traverse properly and the scans will not image the subsurface correctly. The second guiding question asks the user to consider if there is signal interference at the site due to radio frequencies and wireless communication networks. GPR antennas will collect data from all surrounding frequencies, not just the ones that they emit. Because of this, operators should know that scanning near airport communication towers, hospitals, or cell phones will alter the survey results. The third guiding question asks the user to consider how saturated the area or subsurface may be and if so, whether it is fresh or seawater. If an area is uncharacteristically saturated, operators should consider delaying the scan until it has dried out. If the area is constantly saturated, operators should factor the effect of water into their calibration. The fourth guiding question asks the user to consider if the ground has recently been disturbed. Air pockets complicate signal velocity measurements, and surveys should be performed before starting to excavate an area. Additionally, if operators want to test GPR at a recently disturbed location they should take measures to first ensure that the soil is properly compacted.

Object properties will determine how complicated a survey will be and the likelihood of its success. The first guiding question for users to determine if GPR will work for the project asks them to consider the likelihood of the antenna registering the object based on its size, depth, and orientation. The larger the object, the easier it will be to identify and locate. Operators should adjust their expectations if seeking small objects at a significant depth or vertical instead of horizontal pipes. The second guiding question asks the user to consider the differences between the material properties of the object and the subsurface. It is reasonable to assume that objects with

vastly different properties than their surrounding subsurface, like metals in sand, will be located more easily than objects with similar properties, like water tables in clay.

6.4.5.1.4 | *Is Operating In-House or Hiring Consultants Better?*

Once users have determined that they are interested in implementing GPR, the next thing to decide is if the survey should be conducted in-house or by hired consultants. The first guiding question about this asks the user to consider if the project is a routine or uncommon occurrence. For unique or complicated projects, consultants are likely the better choice and use of resources. Operating in-house is likely the more cost-effective choice for routine projects that they are interested in using GPR for permanently. The second guiding question asks the users to consider whether it is more important for them to get quick or precise data. There are scenarios in which inexperienced users and those that currently operate a unit should consider hiring consultants. In situations concerning legal liability disputes, it is more important to obtain high-quality scans than immediate results. Additionally, having an external company take on the liability instead of the in-house surveyors protects municipal employees.

6.4.5.2 | Step 2: Select a Unit

Once the user has evaluated the project needs and decided to purchase and operate in-house, the next step is to select a unit. The first piece of guidance for this is to consider the long and short-term uses of the equipment and the benefits of a dual-frequency antenna when determining the ideal frequency range to choose from. Users are next prompted to use the selection matrices in chapter 4 to create a list of their preferred unit attributes. Having a clear idea of what they are looking for will help them not settle on equipment that won't meet their needs. After assessing the physical attributes of units, users are prompted to consider manufacturer support and long-term

assistance. The last section about how to avoid being taken advantage of during unit demonstrations is based on the advice of the Fayette county interviewees.

6.4.5.3 | Step 3: Secure Funding

Once users know how they would like to implement GPR, the next step is to secure funding for it. This step after selecting a unit so that users consider the price of the unit(s) that best meet their needs or the cost of consultants before requesting funding. The section includes the types of funding sources reported by survey respondents and interview participants.

6.4.5.4 | Step 4: Training

Following selecting a unit, securing funding, and purchasing a unit, the next step is to train operators on how to conduct surveys. The majority of structured training will come from the manufacturer's initial demonstrations. After this, interested operators will need to seek out further training through consultants or continuing education resources by the manufacturer. The majority of training will come from regular use of the equipment and troubleshooting when there are concerns.

6.4.5.5 | Step 5: Implementation

Properly implementing GPR requires more than physically operating a unit. Two essential parts of performing a survey are having a data collection strategy and adequately calibrating the equipment. This step explains why and how to do both.

6.4.5.6 | Step 6: Data Processing

Data processing and analysis is the final step of a GPR survey. For those conducting a survey in-house, the three options are hiring consultants for data analysis and on-site live or post-processing.

6.4.6 | Chapter 6: External Resources

The sixth chapter of the guide introduces users to examples of external resources. The types of resources include those that cover all things GPR, reference texts, and survey guidance materials.

6.4.6.1 | All Things GPR

The first resource for all things GPR is LearnGPR / Bigman Geophysical. This choice is based on their comprehensive and well-supported offerings. Bigman Geophysical offers equipment sales and rentals, training courses, and GPR consultation work. They are a local resource based in Norcross, GA, and provide in-person training and workshops. The second resource is the recommendation of manufacturer websites. Trusted manufacturers like GSSI and Sensors & Software provide detailed information about how GPR works, its applications and case studies, and other technical advice.

6.4.6.2 | Reference Texts

6.4.6.2.1 | *Beginner*

The first literature resource on GPR for beginners is *GPR Basics: A Handbook for Ground Penetrating Radar Users* by Daniel P. Bigman. This book is a part of the LearnGPR curriculum and introduces technical GPR details and methods on a broad scale. The second literature resource on GPR for beginners is *Ground Penetrating Radar Theory and Practice* by Erica Carrick Utsi. This book goes into more technical detail than GPR Basics and offers experienced users more detail on how to improve their approach.

6.4.6.2.2 | *Technical*

The technical texts are less likely to help the average GPR user but are in the guide for those seeking additional information or advanced instruction. These are Ground Penetrating Radar (2nd

Edition) by David J. Daniels and Ground Penetrating Radar: Principles, Procedures, and Applications by A. Peter Annan.

6.4.6.3 | Survey Guidance

For survey guidance, the resources cover GPR parameters and material properties. The first resource is a website called GPR Parameters which helps users plan and execute surveys. It includes a calculator to determine important parameter values, survey requirements, information on what antennas are offered by various manufacturers, and a glossary of terms and equations. The second is the Natural Resources Conservation Service (NRCS) Web Soil Survey. This resource helps users identify the soil type present at survey locations.

6.4.7 | Appendix & Supplemental Information

6.4.7.1 | Appendix

The guide appendix contains two tables. The first is a reference to estimate the size of a wavelength in meters based on the antenna frequency and material RDP. This table is included as a reference so that the guide did not need equations or technical details on how to determine if the signal will register an object. The second table is a complete version of Table 2 from Chapter 2: Saturation for users seeking additional information. The shortened table in the chapter explains the ideal and less effective materials for GPR and omits other standard materials included in the appendix.

6.4.7.2 | Supplemental Information

The guide includes a supplemental acronyms and definitions page to provide users with a curated list of important or complicated terms. The acronyms section includes all of the acronyms used throughout the guide. Each of them is explained the first time it is used, but users reading out of order or referring back to specific portions should not have to search the entire guide for the phrase. The definitions section consists of two types of terms. The first set is the population size

designations used during data collection and referred to in the text. The second set is the terms used frequently throughout the guide and most other GPR literature.

6.5 | Curriculum Review Results

Of the three case study participants, the City of Gainesville and the City of Monroe were the only two to submit their review of the curriculum by the deadline. If and when reviews are received from Athens-Clarke County, their feedback will be taken into consideration in future work.

The execution score is a measure of the quality and accuracy of the information provided. The options are 1 - Poor, 2 - Needs Improvement, 3 - Average, and 4 - Well Done. The relevance score is a measure of the usefulness of the section. The options are 1 - Irrelevant, 2 - Somewhat Irrelevant, 3 - Somewhat Relevant, and 4 - Relevant & Useful. The average execution score given to the guide was 3.77 and the average relevance score was 3.67. Chapter 1 of the guide is the highest rated in both execution and relevance with scores of 3.90 and 3.80 respectively. Chapter 5 of the guide is the lowest rated in execution with a score of 3.71. Chapter 2 of the guide is the lowest rated in relevance with a score of 3.50. Table 12 includes the average score given to each chapter of the curriculum and the average score of all sections and chapters combined.

Table 12: Curriculum Review Results

	Average Execution	Average Relevance
General & Supplemental Information	3.875	3.625
Chapter 1: Introduction	3.9	3.8
Chapter 2: GPR Basics	3.8	3.5
Chapter 3: GPR Applications	3.75	3.75
Chapter 4: Best Practices & Decision Making	3.75	3.75
Tables 3, 4, 5, 6	3.625	3.625
Chapter 5: Getting Started	3.71	3.71
Chapter 6: External Resources	3.75	3.625
Overall Guide Total	3.77	3.67

6.5.1 | General and Supplemental Information

The review section “General and Supplemental Information” received average execution and relevance scores of 3.875 and 3.625 respectively. The sections Guide Overall and Definitions received scores of 4.00 for execution and relevance. The Acronyms section received execution and relevance scores of 4.00 and 3.50 respectively. The section Appendix A received execution and relevance scores of 3.50 and 3.00 respectively. Overall, this indicates that the materials in the Appendix are properly designated as they are relevant, but not relevant and useful enough to include in the body of the guide.

6.5.2 | Chapter 1: Introduction

The review section “Chapter 1: Introduction” received average execution and relevance scores of 3.90 and 3.80 respectively.

6.5.3 | Chapter 2: GPR Basics

The review section “Chapter 2: GPR Basics” received an execution score of 3.80 and a relevance score of 3.50. The comparatively low score for relevance is likely due to the technical nature and detail of these sections. The scores given to chapter 2 for execution and relevance overall are 4.00 each, which disagrees with the actual average scores given to the individual sections. Additionally, one reviewer responded to the written question “Do the figures help explain concepts? (yes or no)” with “Yes” indicating that the figures chosen are beneficial to user understanding. The second reviewer responded “No” however, since this reviewer has experience with GPR, and the other does not, the figures will remain in the guide.

6.5.4 | Chapter 3: GPR Applications

The review section “Chapter 3: GPR Applications” received execution and relevance scores of 3.75 each. The sections Chapter 3: GPR Applications, Historical and Investigative Site Surveys,

and Locating and Mapping Utilities, etc. received execution and relevance scores of 4.00 each. In survey data, site surveys and utility locating were identified as the GPR applications that agencies were the most interested in, so the high score for relevancy aligns with that reasoning. The sections Geology & Hydrology, Concrete Structure Inspections, and Roadways and Pavements received execution and relevance scores of 3.50 each. Again, this rating aligns with survey data on the overall interest in these applications.

Lastly, one reviewer responded to the short answer question “Do you have any other helpful criticism/ comments/ requests related to this chapter?”. In their response, they requested “Additional pictures of the areas and types of materials being scanned by the GPR unit, not just images produced by the GPR unit. i.e. adding more images like Figure 12.” Figures like such were previously searched for to include in the guide, so a potential solution would be to partner with agencies operating GPR units to create original example figures of each. Figure 12 of the guide is shown below in Figure 36.

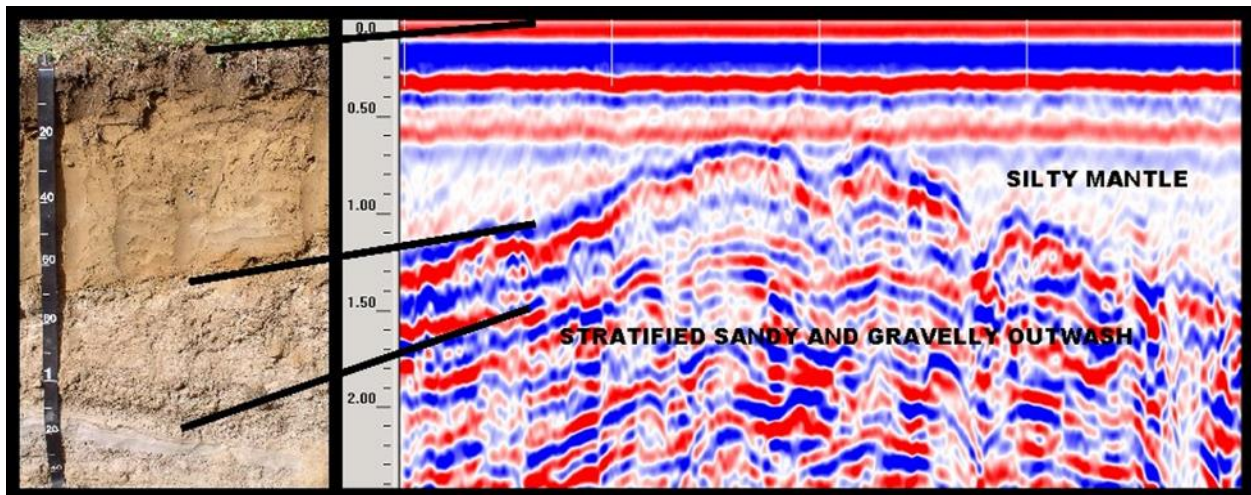


Figure 36: Figure 12 of the *2023 Guide to Ground Penetrating Radar for Local Georgia Agencies*

6.5.5 | Chapter 4: Best Practices & Decision Making

The review section “Chapter 4: Best Practices & Decision Making” received execution and relevance scores of 3.69 each. Additionally, the four tables received average execution and relevance scores of 3.63 each. The sections Chapter 4: Best Practices & Decision Making, Selection of Important GPR Attributes, Table 3: Selection of GPR Unit Type, and Table 4: Example GPR Unit Pricing received execution and relevance scores of 4.00 each. Sections Funding, Training, and Table 6: GPR Antenna Frequency Applications received execution and relevance scores of 3.50 each. The comparatively low scores for Funding and Training are likely a result of the limited information the guide could provide on either topic compared to what was suggested by agencies. Lastly, Table 5: Suggested Method of GPR Procurement received execution and relevance score of 3.00. This suggests that this table would be improved by additional advice and experiential data from agencies.

6.5.6 | Chapter 5: Getting Started

The review section “Chapter 5: Getting Started” received execution and relevance scores of 3.71 each. The sections Chapter 5: Getting Started, Step 1: Evaluate Needs, and Step 4: Training received execution and relevance scores of 4.00 each. The sections Step 2: Selecting a Unit, Step 3: Secure Funding, Step 5: Implementation, and Step 6: Data Processing received execution and relevance scores of 3.50 each. Because this is a key chapter that should only be focused on the needs of agencies, these sections should be reviewed and updated in future work.

6.5.7 | Chapter 6: External Resources

The review section “Chapter 6: External Resources” received execution and relevance scores of 3.75 and 3.63, respectively. The sections Reference Texts and Survey Guidance received execution and relevance scores of 4.00 each.

The section Chapter 6: External Resources received execution and relevance scores of 3.50 and 3.00 respectively. The section All Things GPR received execution and relevance scores of 3.50 each. Because the All Things GPR section received comparatively low scores, future work should evaluate how best to describe these resources and the topics that they cover.

7.0 | CONCLUSIONS

The background and preliminary review for this project identified the potential for municipalities to benefit from implementing GPR and the lack of resources available to help them do so. Survey and interview data further reinforced GPR's potential through the positive experiences that current users have had with the technology. Current users referenced the positive effect that GPR has had on their asset management through decreases in utility damages, increases in surveying efficiency, improvements to their construction coordination abilities, and improvements to their preventative maintenance strategies. Feedback from State level transportation departments to the Federal Highway Administration established the need for support regarding GPR training methods and resources for evaluating the potential usefulness of the technology from an unbiased source other than equipment manufacturers. The existing GPR resources for government agencies are primarily focused on transportation and pavement evaluation. By omitting GPR's ability to contribute to other areas, these resources overlook the majority of its potential as a resource. Interest in GPR continues to grow as it becomes more accessible through improved equipment and updated user-friendly software, so agencies interested in it should have access to information on what it is and how to implement it.

The goal of the curriculum is to improve asset management and help agencies determine how best to focus their resources based on their needs related to GPR applications. The curriculum functions best as a starting resource to educate agencies on what GPR is, how it works, and how to access and implement it. The curriculum provides local agencies with a reference for new and proficient operators to learn from, with or without previous experience. The survey and interview

data were used to identify and outline the curriculum needs and contents. The preliminary review and user experiences were then used to populate the previously established sections. Lastly, the guide was reviewed in a series of case studies to understand and improve the quality of the work and its relevance to local agencies' needs.

7.1 | Recommendations & Future Work

The recommendations and future work for the project are detailed in the following statements.

- Curriculum feedback indicates that the GPR application figures included in the guide would benefit from comparing each radargram to what is being scanned. To achieve this, the researchers could partner with current local GPR operators to collect images.
- The curriculum is limited to suggested uses of a potential resource for inter-municipal and inter-state communication for sharing GPR resources. Further work at the state or federal level is necessary to see this realized.
- Though the developed curriculum is considered up-to-date, GPR technology is an active and ever-evolving industry, so the guide must be updated and adapted over time to maintain its relevant status.

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APPENDIX A: Qualtrics Survey Questions



**UNIVERSITY OF
GEORGIA**

The American Public Works Association (APWA), in collaboration with the University of Georgia College of Engineering and Carl Vinson Institute of Government, is researching the use of Ground Penetrating Radar (GPR) throughout Georgia. The goal of this work is to create a supplemental curriculum and guide on GPR for local governments throughout Georgia and other Georgia APWA members.

This survey is being conducted to gain a better understanding of local Georgia governments' experience with and general interest in GPR.

We appreciate you taking the time to complete this survey. It should take approximately 10 minutes to complete. For any questions, please contact the project's Graduate Research Assistant, Lacy Noerenberg, at lacynoerenberg@uga.edu or (678) 983-1420.

General Agency Information

General Participant Information

Name	<input type="text"/>
Position Title	<input type="text"/>
Contact Email	<input type="text"/>
Phone Number	<input type="text"/>

Which type of agency do you represent?

County

City

Other:

County/City/Town/Municipality Name
(example, for Fulton County, please enter "Fulton")

What is the population within your local government?

Rural < 2,500 people

Small City 2,500 - 20,000 people

Mid-sized (20,000 - 75,000)

Large (> 75,000)

Agency Services and Budget

What is your agency's approximate total budget (in millions of dollars)?

If you cannot represent your budget using the scale, please write it in the textbox.

0 200 400 600 800 1000

Budget (in millions of dollars)



Which services does your local government provide for citizens?

Please select all that apply.

Bridge Inspections

Dam Inspections

Pavement Maintenance and Repair (repaving, fixing potholes and cracking, etc.)

Locating and mapping utility lines, pipes, and underground vaults

Other:

What percentage of the general fund budget is allocated to each of the following?

0 10 20 30 40 50 60 70 80 90 100

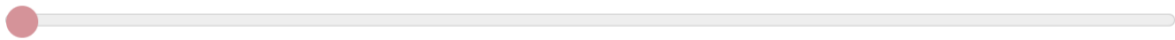
Bridge Inspections



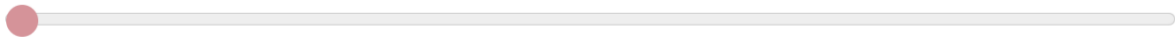
Dam Inspections



Pavement Maintenance and Repair



Locating and mapping utilities



Other:



What percentage of your time is allocated to each of the following?

0 10 20 30 40 50 60 70 80 90 100

Bridge Inspections



Dam Inspections



Pavement Maintenance and Repair



Locating and mapping utilities



Other:



GPR

Is your local government familiar with ground penetrating radar (GPR)?

Yes, we are familiar with GPR and currently own and operate our own unit(s)

Yes, we are familiar with and use GPR, but the work is contracted with private consulting firms

Yes, we are familiar with GPR and its applications, but have not used it before

No, we are not familiar with GPR or its applications

Is your government interested in adopting GPR?

We have already adopted it

Yes, we are very interested in adopting the technology

We are unsure, but would like to learn more

No, we do not see GPR being helpful for our work

Is your local government interested in or currently using GPR for the following applications?

	Not Interested	Interested	Currently Using
Geological exploration (finding depth to bedrock or groundwater, sinkholes and underground cavities, etc.)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Historical and Investigative Site Surveys (cemeteries, etc.)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Locating and mapping utility lines, pipes, underground vaults	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Locating burst or leaking pipes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Concrete, bridge, and/or dam inspections	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Pavement inspections and cracking diagnostics	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
GPR applications not listed above: <input type="text"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Are there any current operations where you would expect your agency to reduce expense or effort by using GPR?

What have been, or are perceived to be, your challenges with the adoption of GPR?

Funding

Training

Selecting a unit

Limiting environmental factors

Other:

If your agency were to adopt the use of GPR, what would be the most accessible/
appropriate training method for your staff? (Please rank in order of most to least
preferable)

Written guide

In person Workshop

Online Module

Other:

Has your agency had a negative experience with GPR? If so, please describe

Current GPR Users

Since you selected that your agency currently owns and operates your own GPR unit(s), please consider answering the following questions.

What type of GPR unit(s) and antenna(s) does your local government use?

How did your agency select your type(s) of GPR unit(s) and antenna(s)?

What type of funding was used to purchase the unit? Did this cover employee training as well?

How were employees trained to use GPR?

Has your agency developed any resources or documentation to support those learning and using GPR technology?

Yes

No

Comments, questions, and concerns

Do you have any additional comments, questions, or concerns?

APPENDIX B: List of Local Government Contacts for Interviews

Large (>75,000)

- Forsyth County Department of Water and Sewer
 - Gary Thurman, Asset Management Specialist
 - GLThurman@forsythco.com
- City of Atlanta Department of Transportation
 - Adisa Aarons, Field Engineer
 - ajaarons@atlantaga.gov
- Brunswick-Glynn County Joint Water and Sewer Commission
 - Todd Kline, Director of Engineering, Planning & Construction Division
 - TKline@bgjwsc.org
- Fayette County
 - Matthew Bergen, Environmental Management Project Manager
 - mbergen@fayettecountyga.gov
- Athens Clarke County
 - Rani Katreeb, Assistant Director of Transportation Public Works
 - Rani.Katreeb@accgov.com

Mid-Sized (20,000 - 75,000)

- City of Valdosta Utilities Department
 - Bradley Eyre, Director of Utilities
 - beyre@valdostacity.com
- City of Gainesville Public Works Department
 - Chris Rotalsky, Public Works Director
 - crotalsky@gainesvillega.gov

Small (< 20,000)

- City of Monroe Utilities Department
 - Ross McMurry, Damage Prevention Supervisor
 - rmcmurry@monroega.gov

APPENDIX C: Guiding Questions for Interviews

General:

- What are the main responsibilities of your position?

Local governments that personally own and operate a GPR unit:

- You indicated that BLANK owns and operates its own GPR unit(s).
 1. What motivated the decision to purchase a unit rather than hire a private contractor for the work?
 - a. Had you hired contractors for GPR work before this?
 2. What unit(s) do you own?
 - a. How was this selected?
 3. What type of funding was used to purchase your unit(s)?
 - a. Optional: How much did it cost to purchase and operate? (Including employee training)
 4. Who, or which department, within your organization is responsible for operating the GPR unit(s)?
 - a. How were employees trained to use the unit and interpret scans?
 - b. Do you have any operation and maintenance or quality control standards in place?
 5. What does your organization use GPR for?
 - a. Are you satisfied with the process and results?

Local governments that hire private contractors for GPR surveys:

- You indicated that BLANK works with private contractors for GPR surveys.
 1. How frequently do you work with GPR contractors?
 - a. On what kinds of projects/ for what types of applications?
 2. How much does this typically cost?
 - a. What type of funding is used to pay for this work?
 3. Has your organization considered purchasing a GPR unit? Why or why not?

Local governments that have never used, or are unfamiliar with, GPR:

- You indicated that BLANK does not currently utilize GPR for surveying
 1. Are you interested in using GPR as a tool for surveying?
 - a. Why or why not?
 2. Has your organization considered using GPR in the past, but ultimately decided against it?
 3. In your survey response, you indicated that your organization would be interested in utilizing GPR for the following: BLANK
 - a. How are these tasks currently performed?
 - b. What are the costs and time spent associated with this method?
 - c. Is this method effective?

APPENDIX D: GPR Guide Review Form

GPR Guide Review Form

Scoring Information

Execution Score:

While scoring for execution, please consider the quality and accuracy of the section.

- 1 - Poor
- 2 - Needs Improvement
- 3 - Average
- 4 - Well Done

Relevance Score:

While scoring for relevance, please consider the usefulness of the section.

- 1 - Irrelevant
- 2 - Somewhat Irrelevant
- 3 - Somewhat Relevant
- 4 - Relevant & Useful

GENERAL & SUPPLEMENTAL INFORMATION

	Execution Score	Relevance Score
Guide Overall		
Acronyms		
Definitions		
Appendix A		

Are there terms that could be better defined?

Are there any terms that should be included in the acronyms or definitions?

Do you have any other helpful criticism/ comments/ requests related to the guide?

CHAPTER 1: INTRODUCTION

	Execution Score	Relevance Score
Chapter 1: Introduction		
Purpose		
Curriculum Justification		
What is GPR?		
GPR for Asset Management		

Do you have any other helpful criticism/ comments/ requests related to this chapter?

CHAPTER 2: GPR BASICS

	Execution Score	Relevance Score
Chapter 2: GPR Basics		
How Does GPR Work?		
Antenna Frequency		
Material Properties		
Calibration		

Do the figures help explain concepts? (yes or no)

Do you have any other helpful criticism/ comments/ requests related to this chapter?

CHAPTER 3: GPR APPLICATIONS

	Execution Score	Relevance Score
Chapter 3: GPR Applications		
Geology & Hydrology		
Historical and Investigative Site Surveys		
Locating and Mapping Utilities, Voids, Storage Tanks, and Underground Vaults		
Concrete Structure Inspections		
Roadway and Pavements		

Do you have any other helpful criticism/ comments/ requests related to this chapter?

CHAPTER 4: BEST PRACTICES & DECISION MAKING

	Execution Score	Relevance Score
Chapter 4: Best Practices and Decision-Making		
Selection of Important GPR Attributes		
Funding		
Training		
Table 3: Selection of GPR Unit Type		
Table 4: Example GPR Unit Pricing		
Table 5: Suggested Method of GPR Procurement		
Table 6: GPR Antenna Frequency Applications		

Do you have any other helpful criticism/ comments/ requests related to this chapter?

CHAPTER 5: GETTING STARTED

	Execution Score	Relevance Score
Chapter 5: Getting Started		
Step 1: Evaluate Needs		
Step 2: Selecting a Unit		
Step 3: Secure Funding		
Step 4: Training		
Step 5: Implementation		
Step 6: Data Processing		

Do you have any other helpful criticism/ comments/ requests related to this chapter?

CHAPTER 6: EXTERNAL RESOURCES

	Execution Score	Relevance Score
Chapter 6: External Resources		
All Things GPR		
Reference Texts		
Survey Guidance		

Do you have any other helpful criticism/ comments/ requests related to this chapter?

APPENDIX E: 2023 *Guide to Ground Penetrating Radar for Local Georgia Agencies*



GROUND PENETRATING RADAR FOR LOCAL GEORGIA GOVERNMENTS

Curriculum Guide 2023

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UNIVERSITY OF GEORGIA



Carl Vinson
Institute of Government
UNIVERSITY OF GEORGIA

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ACRONYMS & DEFINITIONS

ACRONYMS

CAD: Computer Aided Design

GIS: Geographic Information System

GNSS: Global Navigation System Satellite Systems (GPS)

GPR: Ground Penetrating Radar

GPS: Global Positioning System

RDP: Relative Dielectric Permittivity

SUE: Subsurface Utility Engineering

DEFINITIONS

Rural Population: Fewer than 2,499 people.

Small Populations: Between 2,500 and 19,999 people.

Medium Population: Between 20,000 and 74,999 people.

Large Population: More than 75,000 people.

Conductivity: A material's ability to conduct electricity.

Depth & Time Slices: A horizontal GPR radargram.

Heterogeneous Materials: Materials with non-uniform properties.

Homogeneous Materials: Materials with uniform properties.

Radargram: The image produced by the signal reflections.

Relative Dielectric Permittivity: Also referred to as the dielectric constant, how a material holds and responds to an electric charge.

Signal Attenuation: Reduction in signal strength over time because of signal energy loss due to friction.

CHAPTER 1: INTRODUCTION

PURPOSE

Municipal governments must use their employees and general budgets efficiently and effectively to provide services to their citizens. Because of this, it is necessary to have reliable resources at their disposal to assist with asset management. Failure to properly manage assets causes damage to personal property and public infrastructure, but many indicators of this are only detectable using invasive evaluation methods. One of the most widely applicable yet intimidating non-invasive tools for asset evaluation is Ground Penetrating Radar (GPR).

GPR is a non-destructive testing method that can evaluate structures, find utilities, and perform geotechnical investigations.

The goal of this guide is to help educate interested Georgia municipalities on how to access GPR and implement the technology into their work. The purpose of the Guide to Ground Penetrating Radar for Local Georgia Governments is to:

- Educate readers on GPR technology, how it works, and its applications to asset management.
- Offer guidance for selecting and implementing the technology for particular applications.
- Serve as a GPR resource regardless of the end-user's knowledge of the technology.

CURRICULUM JUSTIFICATION

The information and recommendations presented in this guide were developed by researchers within the School of Environmental, Civil, Agricultural, and Mechanical Engineering within the College of Engineering at the University of Georgia. The project was funded by the Georgia Chapter of the American Public Works Association through the University of Georgia's Carl Vinson Institute of Government.

The guide uses qualitative data from a survey on the experiences of local agencies to outline a curriculum curated to meet their needs that is populated using the material from a thorough research review. A survey consisting of municipal populations divided into four categories, Rural (fewer than 2,499 people), Small (2,500 to 19,999 people), Medium (20,000 to 74,999 people), and Large (more than 75,000 people), reported that 19% of

municipal respondents use GPR while 31% reported interest in adopting the technology. A majority of municipalities (42%) reported wanting to learn more about it. [1]

Small agencies have the highest rate of GPR ownership, and large agencies have the lowest. Inversely, large agencies have the highest rate of working with GPR contractors and small agencies the lowest. Georgia agencies' most common use of GPR is locating and mapping utility lines, pipes, and underground vaults. Funding is the most frequent challenge small and medium agencies have with adopting GPR, and large agencies consider theirs to be training and operating.

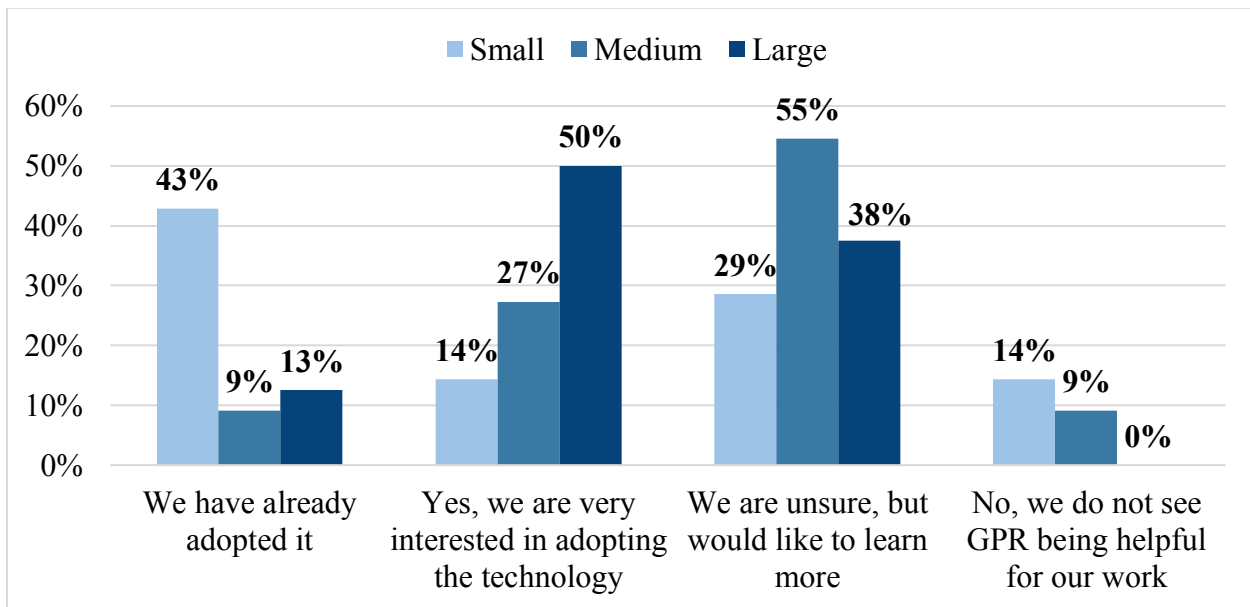


Figure 1: Interest in GPR by Municipality Size [2]

WHAT IS GROUND PENETRATING RADAR?

GPR is a non-invasive surveying technique that uses electromagnetic pulses to detect changes in structural and material features of subsurface composite areas.^[3] GPR's most common use is as a non-destructive geophysical observation tool to find buried objects and obscured geologic features.^[4] Throughout its history, GPR's unique ability to detect any change in material properties means that it can simultaneously survey plastic, metal, fabricated, and natural surfaces.^[5] Because of this, it has been implemented as an archaeological tool to efficiently locate buried artifacts, a method of measuring the depth of ice in glaciers and the distance to underground water tables, and even to study the properties of the moon's crust.^[6] Current applications of GPR in civil engineering include preventative asset monitoring, geotechnical and structural inspections, utility line and vault locating, and informing design choices.^[7]

GPR FOR ASSET MANAGEMENT

GPR's many applications give it the potential to save time, money, and effort in providing the services required of local Georgia Governments. Four key areas of improvement are:

INCREASED SURVEY EFFICIENCY

Modern GPR systems that utilize GNSS technology collect the location data points of identified objects that can be integrated into GIS and CAD files for improved survey efficiency and map accuracy for design.

DECREASED UTILITY DAMAGES

Keeping up-to-date and accurate maps of public utilities decreases the likelihood of damage to them during construction and preventable delays due to design conflicts.

IMPROVED PREVENTATIVE MAINTENANCE

Nondestructive testing allows for more detailed observations than visual infrastructure inspections without causing damage. In roadway inspections, GPR produces a continuous profile of the subsurface subject rather than the traditional localized samples like pavement cores. GPR is significant in asset management due to its ability to identify locations of potential failure across a great distance before warning signs may be present at the surface.

IMPROVED CONSTRUCTION COORDINATION

Identifying signs of distress before failure helps municipalities better prepare their construction budget and plans, giving them the opportunity to improve the coordination of projects throughout their departments.

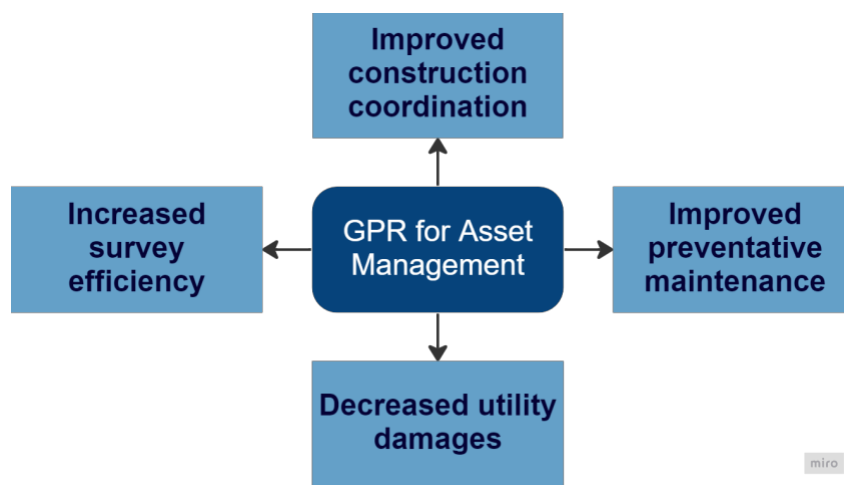


Figure 2: Benefits of Using GPR for Asset Management

CHAPTER 2: GPR BASICS

HOW DOES GROUND PENETRATING RADAR WORK?

WHAT IS A GPR SYSTEM?

Today's GPR systems typically consist of five main components. These components include a control unit, an antenna, an internal or external power supply, a data storage and monitoring device, and a distance measurement device. Recent models often use versatile tablet computers for data monitoring and storage devices. These systems can be relatively small, handheld devices, larger walk-behind units resembling a lawn mower, or mounted on a vehicle for roadway scans.

As shown in Figure 3, the system's antenna has two components, the first for emitting the pulse and the second for receiving its reflection.

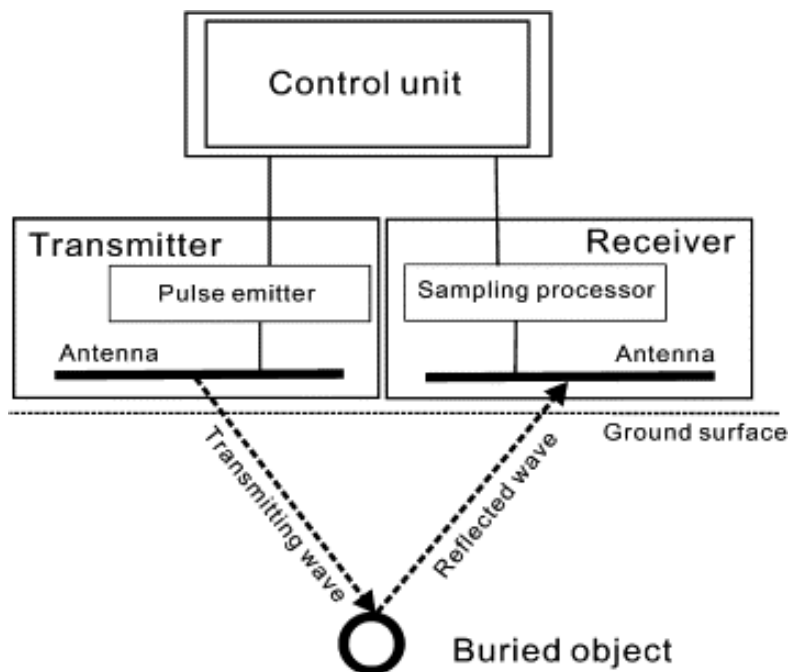


Figure 3: Block Diagram of a GPR Electromagnetic Pulse ^[8]

HOW ARE IMAGES CREATED?

As the pulse travels through the subsurface, part of the signal reflects to the receiver each time it experiences a change in material properties like conductivity and dielectric constant. (See Chapter 2: "Material Properties" for more information on conductivity and dielectric constants). Layering all the reflections at a point creates a one-dimensional view

of material variations. The two-dimensional images are formed when multiple pulses are emitted across a certain distance. This process is shown in Figure 4 where the “point reflector” represents a buried object, and the “plane reflector” represents a point where two ground materials meet. “Tx” represents the location where the signal is emitted, and “Rx” represents where it is received. GPR measures the depth to objects using the signal’s velocity as it travels through the subsurface. [9] [10]

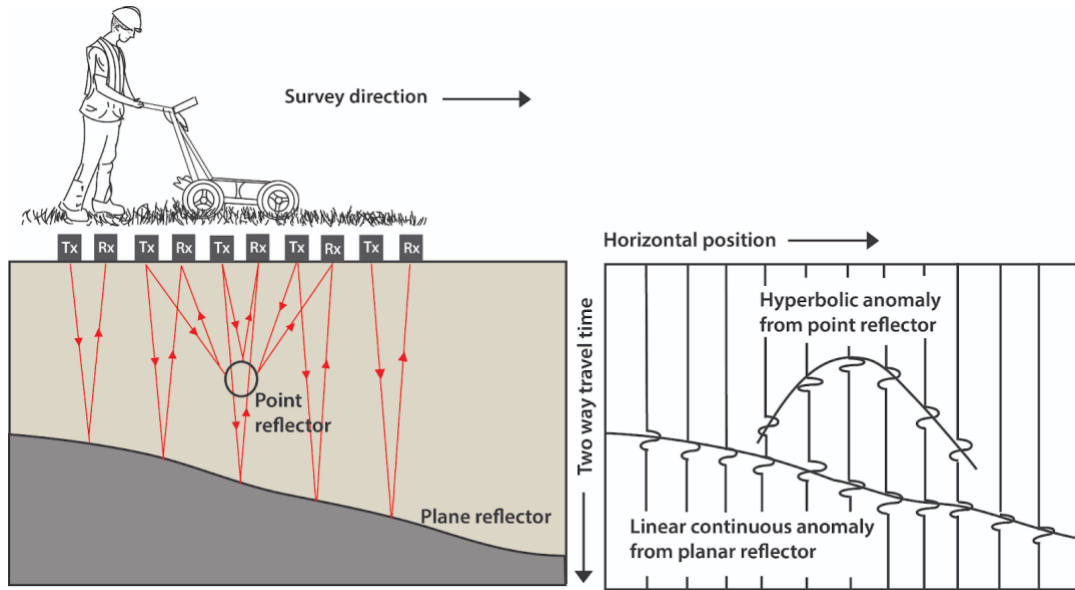


Figure 4: GPR imaging method [11]

WHY DO OBJECTS SHOW UP AS HYPERBOLAS?

The hyperbolic shape of symmetrical objects is a result of the signal’s cone-shaped footprint. The circular footprint, shown in Figure 5a, means that the signal registers the presence of an object or change in material properties for a certain distance before and after it is directly above it. The signal’s pathway, represented by the solid lines in Figure 5b, is how GPR measures the depth of an object. If the object in Figure 5 is metal, the signal wave cannot pass through to measure the depth to Layer 1 along the same path as it does the object. [12][13] (See Chapter 2: “Material Properties” for more information on the influence of material properties on scans). In Figure 5c, r_1 , r_2 , and r_3 represent the measured depths of the object from each of the three antenna locations. Shown in Figure 5d, the depth measurements (r) are next projected as vertical lines. An arc, as is shown in Figure 5e, is drawn to connect the points resulting in the final hyperbolic image of Figure 5f.

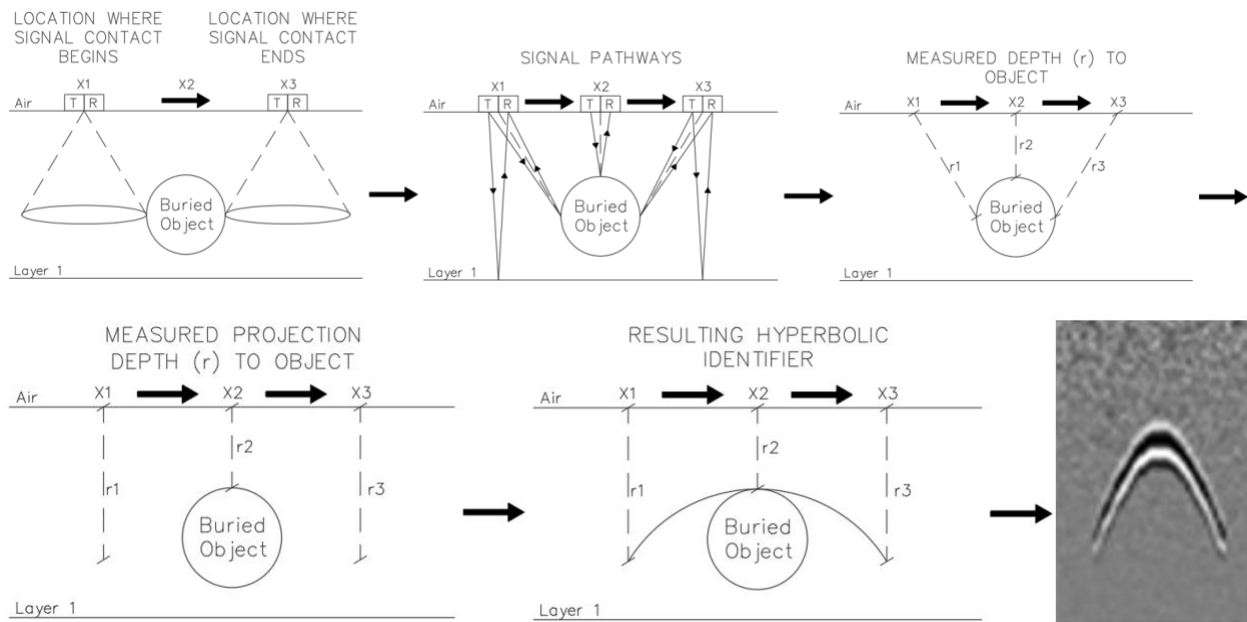


Figure 5 a, b, c, d, e, & f: Steps to generating a hyperbolic reflection [12]

HOW CAN GPR CREATE 3D IMAGES?

GPR has an advantage over other geophysical mapping methods because it can collect, measure, and model data in three dimensions, like Figure 6. Horizontal views, also known as time or depth slices, allow surveyors to track the path of objects like pipes and utilities. Additionally, in the case of a densely populated subsurface, time slices help differentiate between closely spaced parallel objects and determine which follow a linear path like pipes and which do not.^[9] The term fence diagram refers to the collection of vertical images.

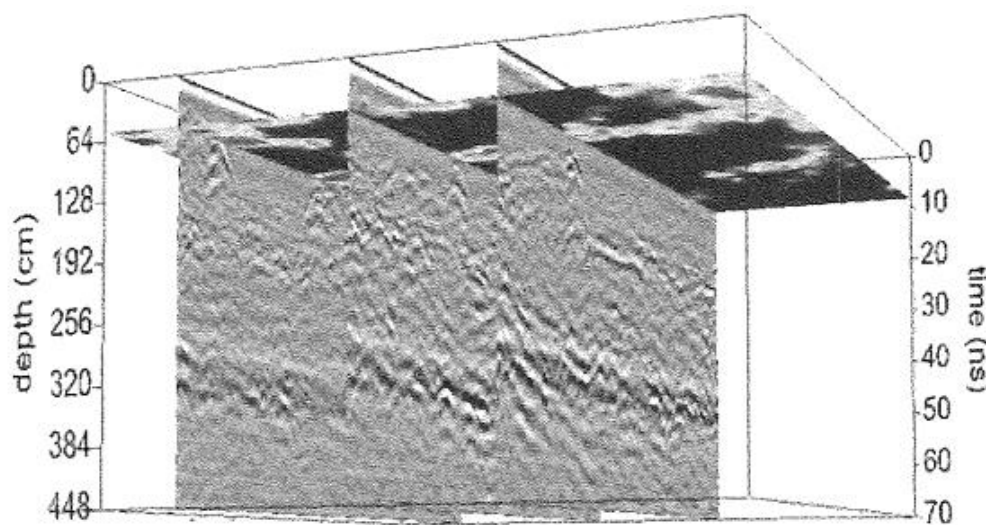


Figure 6: Fence Diagram with Time Slice [9]

Time slices are created by interpolating data from 2D vertical profiles that repeatedly identify an object at the same depth and location across several profiles. The accuracy of the scan will improve with the inclusion of survey data along a grid traveling in superimposed East to West and North to South directions. The second direction improves horizontal tracking and helps minimize error. The system model and software will determine how it forms time slices.

HOW LONG WILL IT TAKE TO GET THE RESULTS?

GPR data can process results in real-time, or if it requires a more detailed analysis, after the survey. A system's real-time processing capabilities depend on the manufacturer and unit and may include manipulatable 3D models.

WHAT INFLUENCES THE SUCCESS OF A GPR SURVEY?

The accuracy of a GPR survey depends on the properties of the material it travels through, the existence of buried or obscured surfaces, and the frequency of the antenna(s) used. If the proper steps are not taken to consider the technical details of the survey, the results will be unreliable or unusable. Improper calibration for a surface saturated with water may lead to complete signal attenuation, or choosing the wrong antenna frequency may lead to the survey being unable to reach the intended target or obscuring subsurface obstacles.

ANTENNA FREQUENCY

Selecting the ideal antenna frequency for a survey depends on two features, the preferred survey penetration and resolution depth. The penetration depth is the vertical distance to which the signal can collect data. The resolution depth is the depth to which the signal can identify and differentiate between two closely spaced objects.^[14] A higher frequency creates shorter wavelengths, which are absorbed faster than a lower frequency wavelength. (See Appendix A: Table 7 for the estimated wavelength size in meters based on RDP and antenna frequency). The shorter transmission time of the high-frequency wavelength creates a more detailed image than a low-frequency antenna but reaches a shallower depth. As the antenna frequency decreases, the penetration depth increases, but the quality and detail of the image decrease.^{[9][15]} Because of this, when selecting an antenna, use the highest frequency still capable of reaching the necessary depth. (See Chapter 4: Table 6 for examples of the appropriate applications and approximate depth range of antenna frequencies).

It is important when selecting the antenna for a project that the size of the wavelength is smaller than the object(s) being measured. If surveying an area with unknown contents, multiple scans using different antennas should be performed so that objects too small to

be detected by a low-frequency antenna are not missed and vice versa. Though high-frequency antennas are the best for depicting shallow areas such as structural concrete, bridge decks, pavements, or other objects close to the surface, their short penetration depth limits the applicability of the scans. The resources featured in Chapter 6 include examples of how to determine if the frequency will work for an object size.

Dual-frequency antennas are a beneficial tool to those interested in owning a single unit for a variety of applications or for projects that require high (measuring pavement layer thickness) and low (utility locating) frequencies. A project may require both if the operator wants a scan precise enough to image the contents of a shallow subsurface while reaching a greater depth than the high-frequency antenna can manage.^[9] Scanning the same section twice with two individual antennas can produce a similar result, but the operator must ensure that the scans will align in location and timing. Figure 7 is two scans taken simultaneously by a 250 MHz and 700 MHz dual-frequency antenna. The coarse image produced by the 250 MHz channel reaches a depth of 6.00 m (19.69 ft) while the fine image produced by the 700 MHz channel reaches a depth of 2.00 m (6.56 ft).

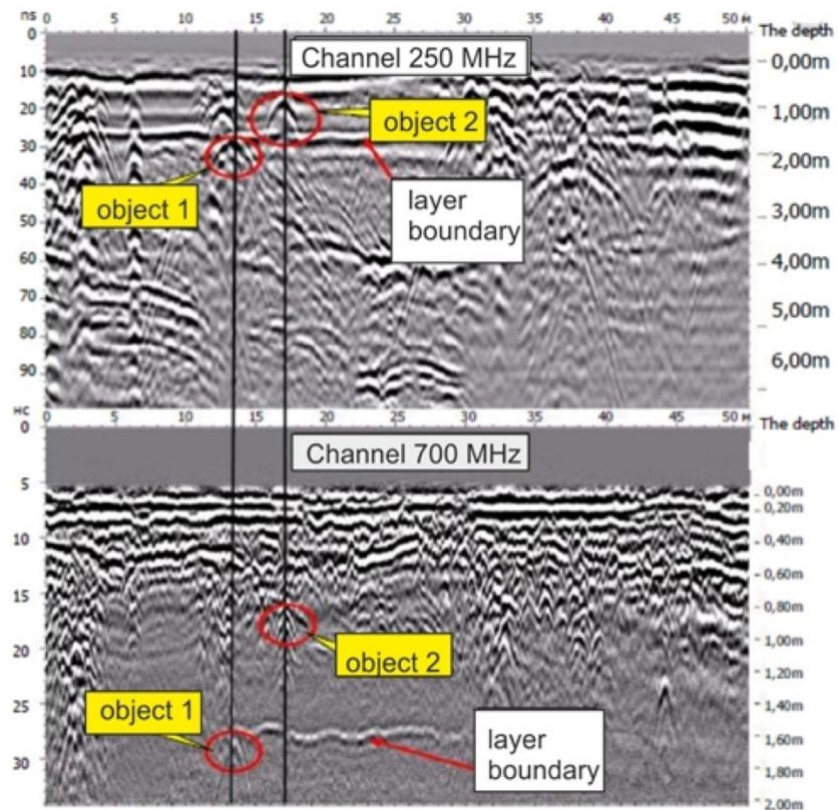


Figure 7: Scan performed by a 250 MHz and 700 MHz dual-frequency antenna ^[16]

Antenna Scenario #1: Low-Frequency

Residents of a city would like to have the option of purchasing plots in the historical part of the local cemetery. Though there appears to be plenty of space available, the cemetery authority is unsure of the number of unmarked and undocumented graves in the area. To locate them, a low-frequency GPR unit (around 400 MHz) can be used to identify large voids and metal coffins between 0 to 12 feet below ground.

Antenna Scenario #2: High-Frequency

A structure is being updated to include new utilities. Running the pipes and wires will require drilling through one-foot-thick reinforced concrete. Damage to the reinforcement will likely cause construction delays and unnecessary expense, so they need to determine rebar locations and spacing before deciding where to cut. To do so, a handheld GPR unit with the highest-frequency antenna available (around 2600 MHz) should be used to image the reinforcement and determine safe drilling locations.

Antenna Scenario #3: Dual-Frequency

Part of a roadway has cracked again despite its recent repair. The section has had repeated cracking problems, and the costs of the frequent fixes are adding up. A dual-frequency GPR unit is used to help diagnose the issue so that there is a detailed scan of the pavement and a coarse scan of the soil beneath it. If necessary, the shallow scan of the pavement layers can be verified by pavement coring.

MATERIAL PROPERTIES

The electromagnetic properties of the subsurface and object materials influence the antenna wavelength's velocity.^[10] These properties, the dielectric permittivity, electrical conductivity, and magnetic permeability, are a measure of the soil and rock matter, water content, and bulk density of the material.^[9]

Of the three, the functionality of a GPR survey depends on the relationship between the material's dielectric constant and electrical conductivity.

RELATIVE DIELECTRIC PERMITTIVITY (RDP)

- Indicator of how a material behaves when introduced to an electric field.
- The lower the RDP, the higher the velocity of the wavelength through the material.
- Also referred to as the Dielectric Constant in GPR-related content.

ELECTRICAL CONDUCTIVITY

- How well a material conducts electricity.
- Increased conductivity causes an increased rate of signal attenuation.
- Signal Attenuation: Reduction in signal strength over time because of signal energy loss due to friction.

It is unnecessary to have a complete and complex understanding of RDP and Conductivity to use GPR, but it is important to know why and how they influence the signal's velocity and measurement accuracy. Tables 1 and 2 include the velocity of commonly surveyed materials and the effect of RDP and conductivity on signal properties, and the approximate RDP and conductivity of common materials. Ideal materials for GPR have a low RDP and low conductivity because these conditions mean that the signal will reach a greater depth by traveling quickly while losing minimal signal strength.^{[9][10]}

Table 1: Effect of RDP and Conductivity on Signal Properties ^[9]

		Low RDP	High RDP
Low Conductivity	Penetration Depth:	↑	-
	Wavelength Velocity:	↑	↓
	Signal Attenuation:	↓	↓
	Example Material(s):	Dry Sand Granite Bedrock	Lakebeds Freshwater Tables
High Conductivity	Penetration Depth:	-	↓
	Wavelength Velocity:	↑	↓
	Signal Attenuation:	↑	↑
	Examples Material(s):	Gasoline	Saltwater

HETEROGENEITY

The heterogeneity, or diversity, of a material in an area, will influence if and how well a survey can be performed there. When searching for an object, it is ideal for it to have very different material properties than the surrounding substance because it will improve the clarity of the scans and make the layer boundaries more distinct. However, the more heterogeneous the surrounding substance, the more difficult to observe on the survey. As is discussed in Chapter 2: “How are images created?” the signal reflects at every change in the material it experiences, so traveling through a heterogeneous substance will cause the scan to pick up excessive data and clutter a scan like in Figure 8.

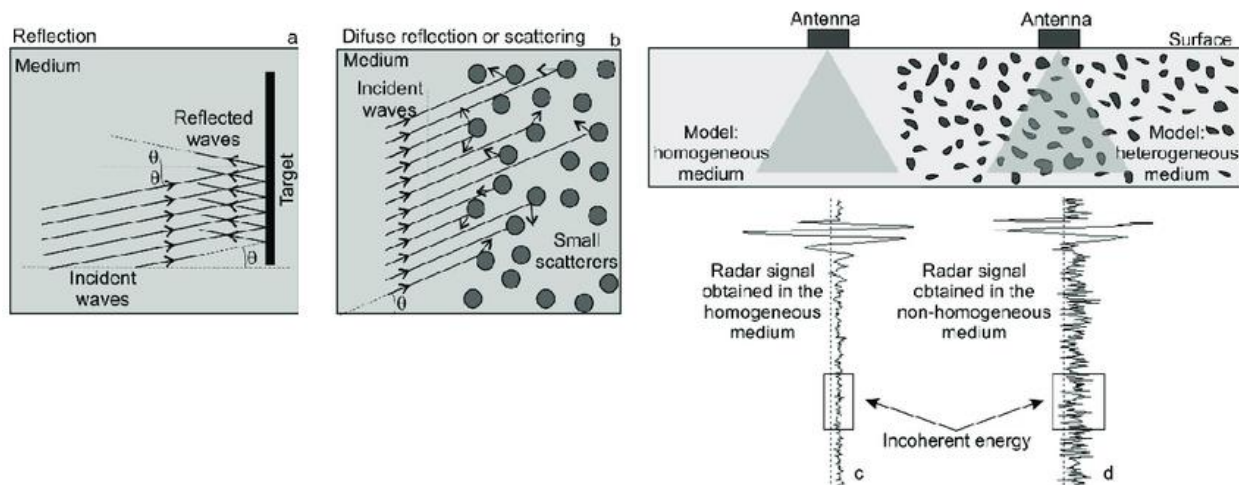


Figure 8: Radar signal in a modeled homogeneous and heterogeneous material [17]

In addition to a diversity of materials in the substance, a site’s subsurface will rarely be homogeneous throughout the scan area. If there are differences across the site, it is necessary to calibrate for each to maintain survey quality. Take, for example, a survey of a water table beneath granite in one area and clay in the other. Due to their vastly different RDP and conductivity, shown in Table 2, the surveyor needs to know where it switches to accommodate the difference in wavelength size caused by the change. The water content in the clay results in less change in properties registered between it and the water than between granite and the water.^[18] As a result, the water table will reflect more clearly through the granite than through the clay.

SATURATION

As mentioned in the previous clay example, saturation significantly impacts how to perform a GPR survey. Table 2 includes the properties of dry and saturated sand, which have an RDP difference between 15 – 27 and a 0.09 m/ns difference in average velocities. These differences mean that a survey area will have significantly different properties before and after rainfall. The decreased signal velocity due to water means that a fully

saturated soil will require a larger wavelength and penetration depth to reach and image the same object as it would in an unsaturated environment like the compact construction fill in Figure 9.^{[9][10]}

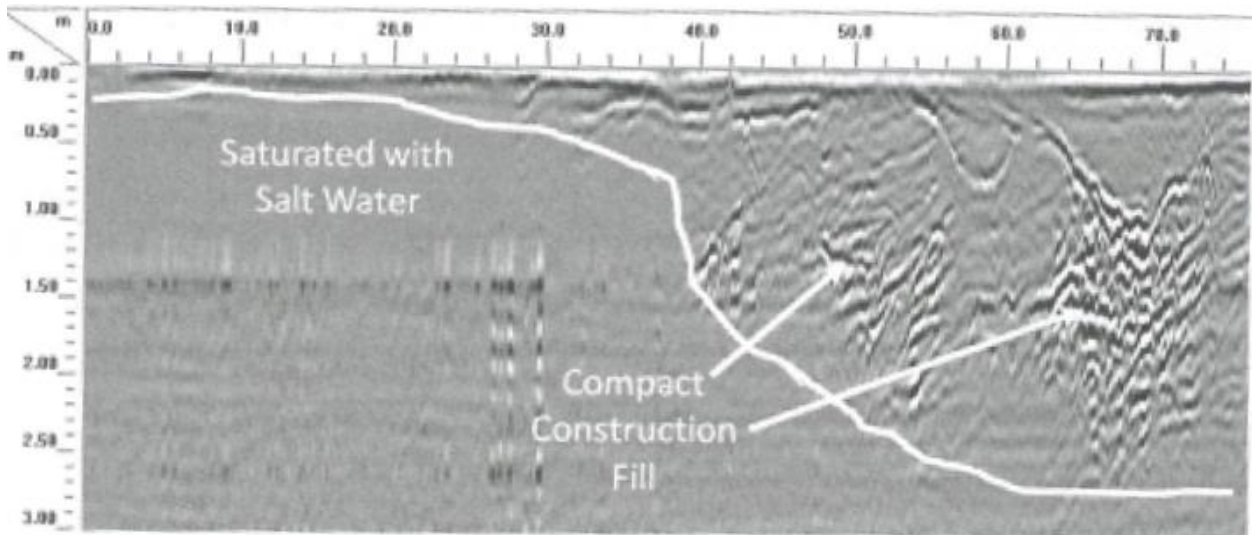


Figure 9: Signal attenuation due to saltwater saturation ^[9]

As shown in Figure 10, water content affects how a pipe will appear depending on whether or not there is water or sewage present. In the steel pipe with freshwater inside (Figure 10b), the signal amplitude decreases due to the water.

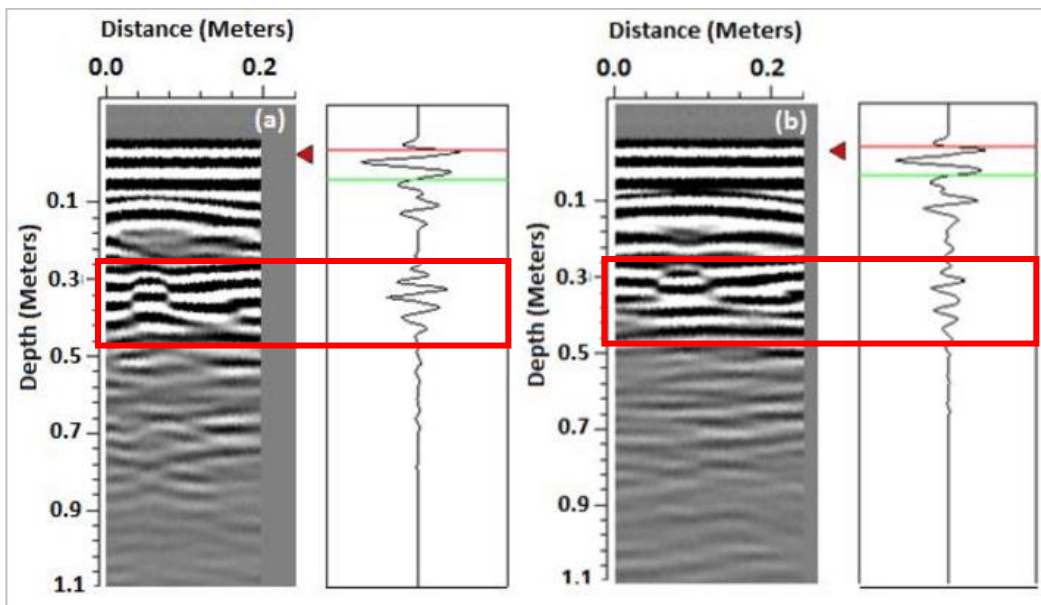


Figure 10: Data of a) empty steel pipe and b) steel pipe with freshwater inside ^[19]

METALS

Tables 1 and 2 do not include types of metallic materials because their RDPs are not calculated or considered in calibration decision-making. Metals have an RDP close to infinity and are complete reflectors that do not allow wave energy to pass through them.^[9] Total reflection means that GPR cannot detect anything directly below the object in the "shadow" zone where the signal cannot reach. Figure 11 shows two radargrams, one with five metal and one with five plastic objects. In Figure 11a, the object hyperbolas are defined clearly and do not show as many changes in material properties below them as in Figure 11b. Unless the wavelength is small enough to pass through gaps between pieces of metal, anything below metal sheets, fine metal mesh, or pan decking will not be visible to a GPR survey.

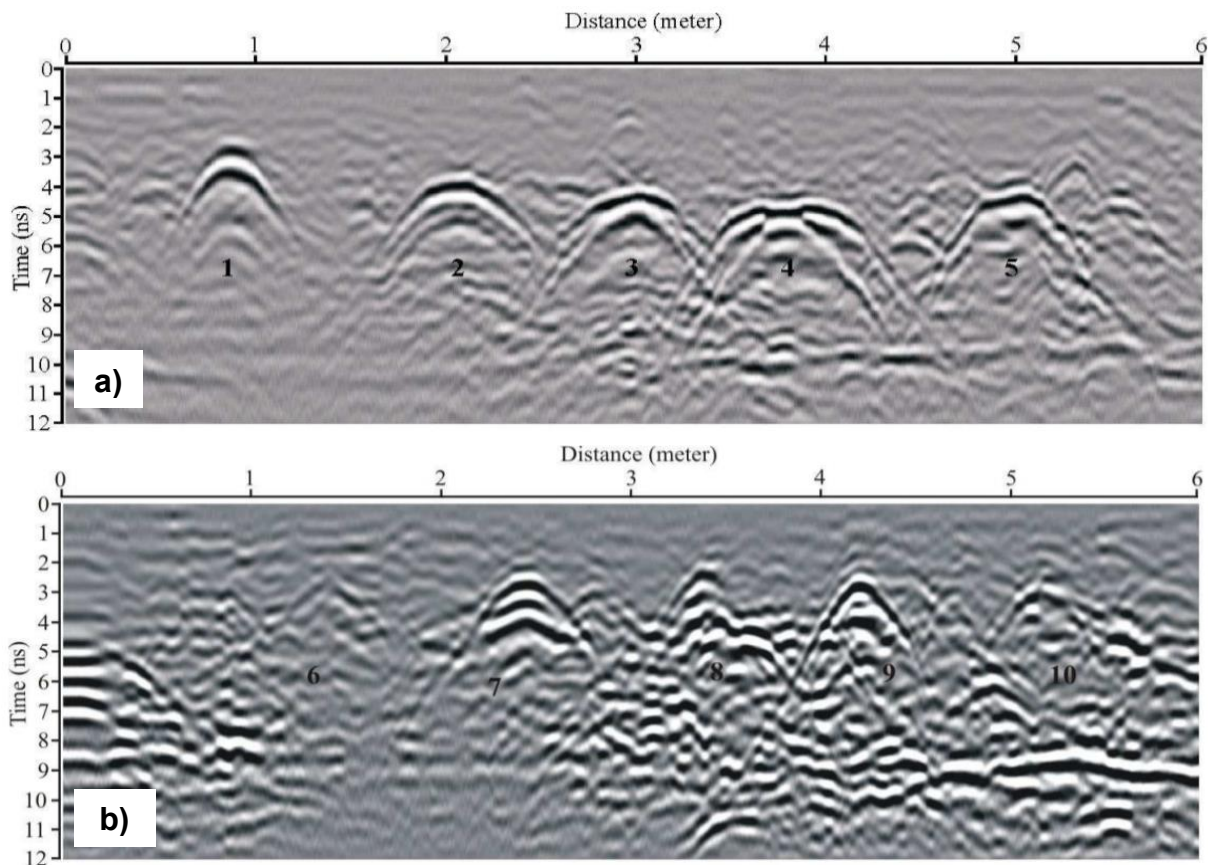


Figure 11: Comparison of a) metallic and b) plastic object radargrams ^[20]

CALIBRATION

Designing a survey and adjusting equipment will vary between unit manufacturers, but it helps if the operator understands the reasons for calibration. When a GPR survey measures the depth of an object, time data is recorded rather than distance data and

used to determine depth. This calculation relates the estimated signal velocity through the material to the time it takes the signal to be emitted and reflected to the receiving antenna. The signal velocity (in meters per nanosecond) multiplied by the recorded time (in nanoseconds) gives two times the estimated depth value (in meters). Because it relies on the signal velocity value, it is necessary to calibrate the system to the most accurate material properties possible so that it calculates the correct depth.

It is helpful for the operator to make observations and provide site-specific inputs; however, much of the survey calibration happens through the GPR unit's software. The simplest way to approach calibration is to use estimated standard table values of material properties, like those in Table 2. These values are appropriate starting values but are not specific enough to ensure measurement accuracy. Two standard methods of calibrating a scan to a site are using a known depth to an object and hyperbola fitting.

Known depth to object is a method that uses the scan time of an object with a recorded depth to calculate the signal velocity through the ground material. For example, scanning a pavement and comparing the scan to the thickness of a cored pavement sample. Hyperbola fitting uses the properties of manufactured hyperbolas that “match” the hyperbolas of a scan to estimate material properties.^{[9][10]} This process is dependent on software and is explained further by the resources in Chapter 6.

Table 2: The Approximate RDP, Conductivity, & Signal Velocity of Common Materials

Ideal Materials for GPR			
Material	Relative Permittivity	Conductivity [μS/ft]	Average Velocity [ft/ns]
Air	1	0	0.984
Ice	3-4	3.05	0.525
Dry Sand	3-5	3.05	0.492
Granite	4-6	3.05 - 304.8	0.427
Less Effective Materials for GPR			
Material	Relative Permittivity	Conductivity [μS/ft]	Average Velocity [ft/ns]
Saturated Sand	20-30	30.5 - 304.8	0.197
Clays	5-40	610 – 304,800	0.197
Freshwater	80-81	152.4	0.108
Seawater	80-81	914,400	0.033

CHAPTER 3: GPR APPLICATIONS

GEORGIA APPLICATION EXAMPLES

Below are four examples of how local Georgia agencies currently use GPR.

Application 1: Non-Conductive Object Locating

Local Georgia agencies are currently using GPR to locate non-conductive pipes. GPR serves as the primary or alternate solution to locating hard-to-find infrastructure like pipes without tracer wire, clay pipes, and PVC pipes without digging potholes. Additionally, it can be used as a backup tool if no adequate GPS coordinates are available or if the traditional surveying method's results are inconclusive.

Application 2: Subsurface Utility Engineering (SUE)

A current application of GPR by local Georgia agencies is for subsurface utility engineering (SUE). Using GPR to identify the locations and directions of existing utilities helps avoid conflicts during new utility placement. Cost-savings are achieved through better designs that accommodate the existing infrastructure and determining whether relocations are necessary early rather than mid-construction.

Application 3: More Efficient Asset Mapping

GPR is used by local Georgia agencies for mapping public assets. Depending on the system, GPR units equipped with surveying technology can locate and map assets within centimeter accuracy. This capability improves the data quality and decreases the time necessary for data collection.

Application 4: Roadway Inspection

Local Georgia agencies use GPR for roadway inspections. These inspections include using GPR to supplement coring and borehole test results for pavement assessments and bridge deck monitoring. Additionally, GPR is used to survey pavement subgrade to determine soil properties and identify voids.

EXPECTED OUTCOMES

Depending on the quality of calibration and survey collection strategy, GPR can determine the following.

LOCATION

GPR locates objects and voids by identifying where there are changes in the material properties of a subsurface.

DEPTH

GPR measures the depth to objects and potential voids by recording the time it takes for the signal to travel from the antenna transmitter to the receiver. It is important to note that it does not measure a physical distance but instead calculates a distance based on how the signal behaves in the material and how well the unit is calibrated.

THICKNESS

GPR measures thickness similarly to how it measures depth to an object. GPR can record the object or material layer thickness by converting the signal velocity and duration spent traveling through each material to a distance value.

DIMENSION

GPR measures the dimension of an object using the size of the signal footprint at its depth and when it first and last senses the difference in the material properties. This can measure pipe radii and identify the utility type as well as measure the size of objects and voids.

ORIENTATION

GPR determines an object's orientation and the direction it travels in. This is determined using the linear interpolation of scans that repeatedly register the presence of an object at the same depth across a distance. GPR can image concrete reinforcement or map pipe pathways.

ELECTRICAL PROPERTIES

GPR identifies the electrical properties of a subsurface by observing how the signal behaves while traveling through it and ultimately calculates soil properties like water content, density, and stiffness using the dielectric constant it measures.

LIMITATIONS

The effects that limit the quality of GPR outcomes include attenuation effects like saturation, signal blockage by complete reflectors, and trace interval sizes.

GEOLOGY & HYDROLOGY

Using GPR to survey geologic and hydrologic features creates a more accurate map of soil strata than methods like soil coring that only represent the features present at the precise location sampled.

SOIL EXPLORATION

MAPPING SOIL AND MINERAL DEPOSITS

Even with little data processing, GPR profiles of soil strata below plain ground or freshwater bodies can be high-quality qualitative data for hydrogeologic studies. With or without precise depth and thickness measurements, using GPR to profile layers of subsurface soil and rock helps prevent the unnecessary destruction of natural features.^[21]

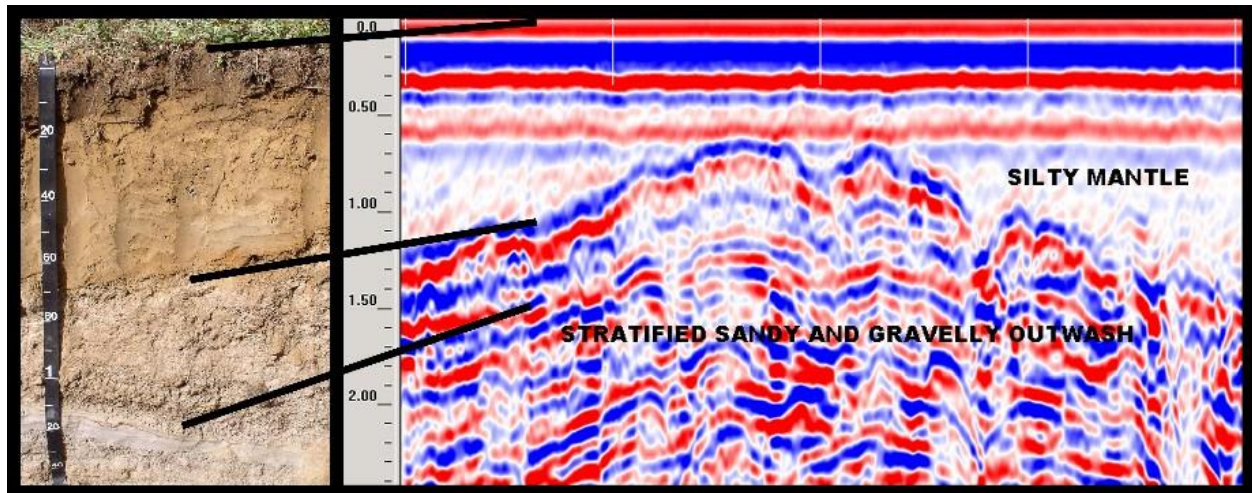


Figure 12: GPR profile showing the discontinuity separating two soil types ^[22]

SOIL PROPERTIES TESTING

The data from GPR surveys can mathematically estimate soil properties such as water content, bulk density, and stiffness. These are calculated using the relationships between the wavelength velocity through a material, its dielectric permittivity, and the volumetric properties of soil components.^{[23][24][25]} These properties are relevant to geotechnical land surveys, precision agriculture, and pavement design and monitoring. Figure 13 shows the subgrade survey scan results of a 650-foot length of pavement. The estimated dry density using GPR data at three points of concern aligns with the value calculated using traditional soil density testing methods. In addition, the GPR dry density data indicate locations along this length of pavement that, if not already showing signs of failure due to low soil density, will begin to fail soon.

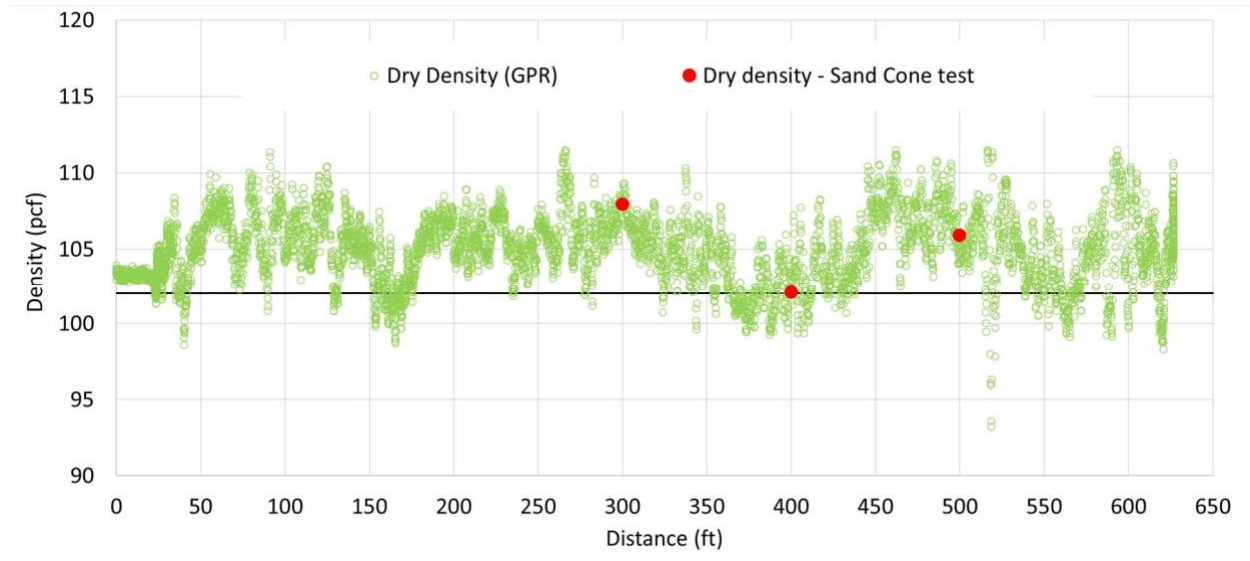


Figure 13: Dry Density Calculated Using GPR versus Sand Cone Test [23]

GROUNDWATER MONITORING

As a state with many significant freshwater sources, Georgia has a responsibility to maintain and protect its aquifers and rivers. GPR is a valuable resource for this and can be applied to locate water tables, measure soil water content, monitor groundwater, and detect and map contaminates. GPR can be used as a noninvasive method to determine the elevation of shallow water tables, saturation levels of underground pores, and the flow path of the water.^{[26][27][28]}

Tracking water patterns and changes in subsurface saturation is possible because of the influence that water has on the velocity of a wavelength. The variation in wavelength velocities across routine scans of a water table will indicate degrees of saturation, or other types of underground pores, compared to differences in factors like heavy rainfall or drought. As discussed in Chapter 2: Section "Material Properties" the rapid signal attenuation through water results in profiles like Figure 14, where the scan quality deteriorates after passing through a water table. While this phenomenon makes it difficult to survey below saturated areas, it means that GPR can locate burst or leaking pipes due to uncharacteristic changes in subsurface properties shown in Figure 15.

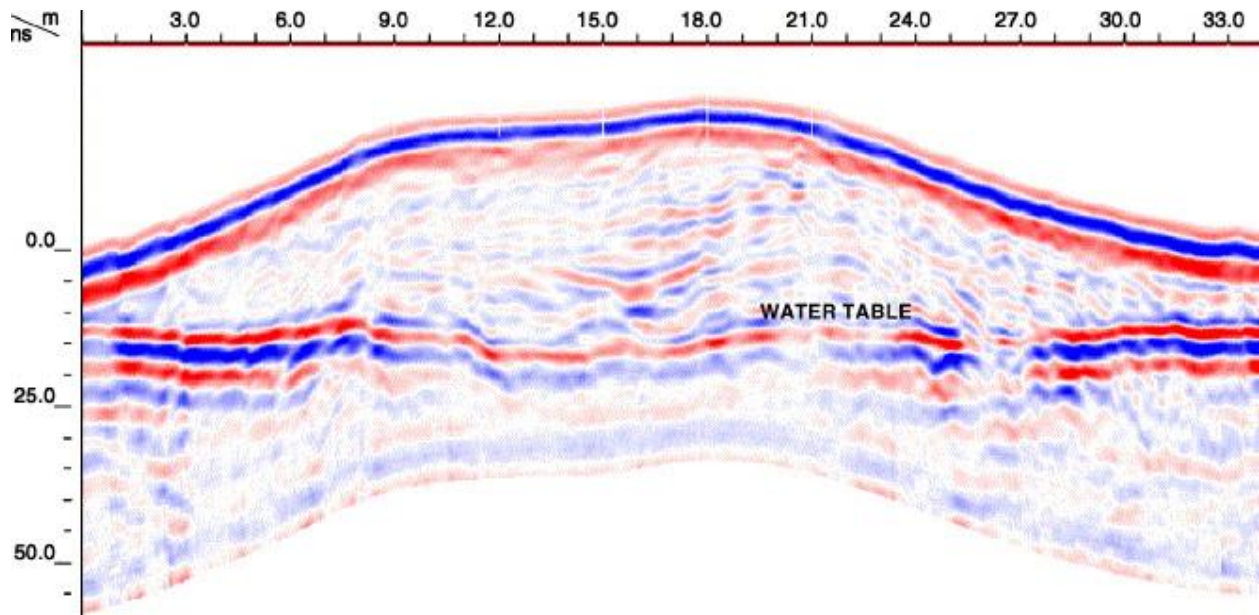


Figure 14: A 200MHz GPR profile of a low eolian dune including a water table [29]

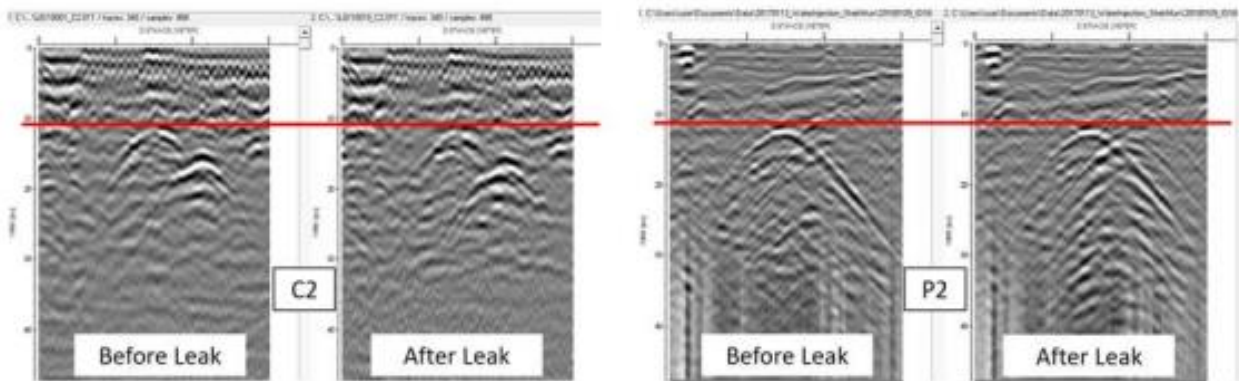


Figure 15: GPR scans of two locations before and after water leak simulation [30]

FORESTRY

Forestry applications of GPR are beneficial to conservation efforts and can assist in avoiding damage to the root systems of significant trees. Additionally, GPR can identify if damage to public infrastructure, like pavement cracking, is due to tree roots.

HISTORICAL AND INVESTIGATIVE SITE SURVEYS

When surveyed, 61% of Georgia municipalities report they are either interested in or currently using GPR for historical and investigative site surveys. GPR is a valuable resource for these as it can identify potential dig sites and structurally significant elements before excavation and accurately survey areas that should be left undisturbed.^[31] For

many local Georgia agencies, their interest in this application is for improved cemetery mapping, maintenance, and management. Others identified this and geological exploration as potentially beneficial to their design and construction of public assets.

HISTORICAL STRUCTURES

For surveys of historical buildings, GPR can assess and indicate damage to columns or walls and identify unique structural design elements. This information can benefit future restoration efforts, anticipate and prevent potential failures, and highlight the significance or uniqueness of its properties. Figure 16 show the GPR image of the fourteenth-century Santa Maria del Mar church roof in Barcelona, Spain.

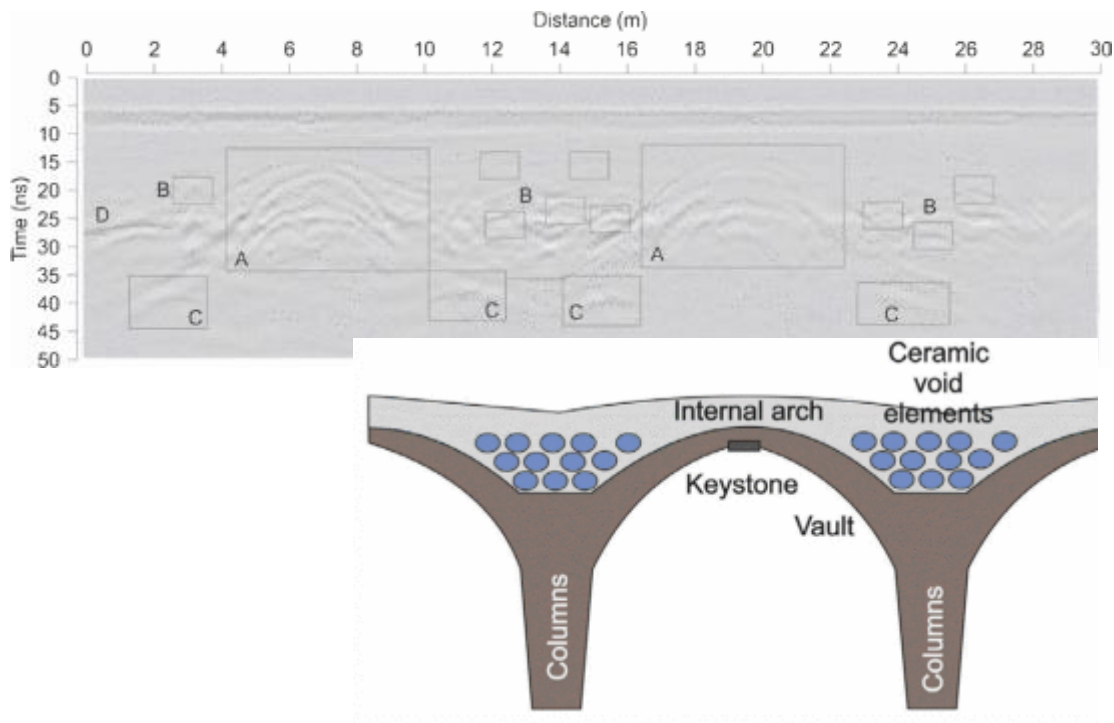


Figure 16: Possible interpretation of the roof subsurface between two columns. A) reflections on the vaults. B) reflections on heterogeneous material and voids between vaults. C) reflections on column capitals supporting vaults. D) reflection on homogeneous material between the vaults and wall.^[32]

ARCHAEOLOGY

CEMETERIES, LOCATING AREAS OF SIGNIFICANCE, FORENSICS

GPR is a valuable tool for archaeological explorations of developed and undeveloped sites. At either site type, GPR can locate structural elements and artifacts without the risk of damaging them. In addition to open land surveying, GPR is used at developed locations to explore the ground in and around buildings or other structures, as shown in Figures 17.

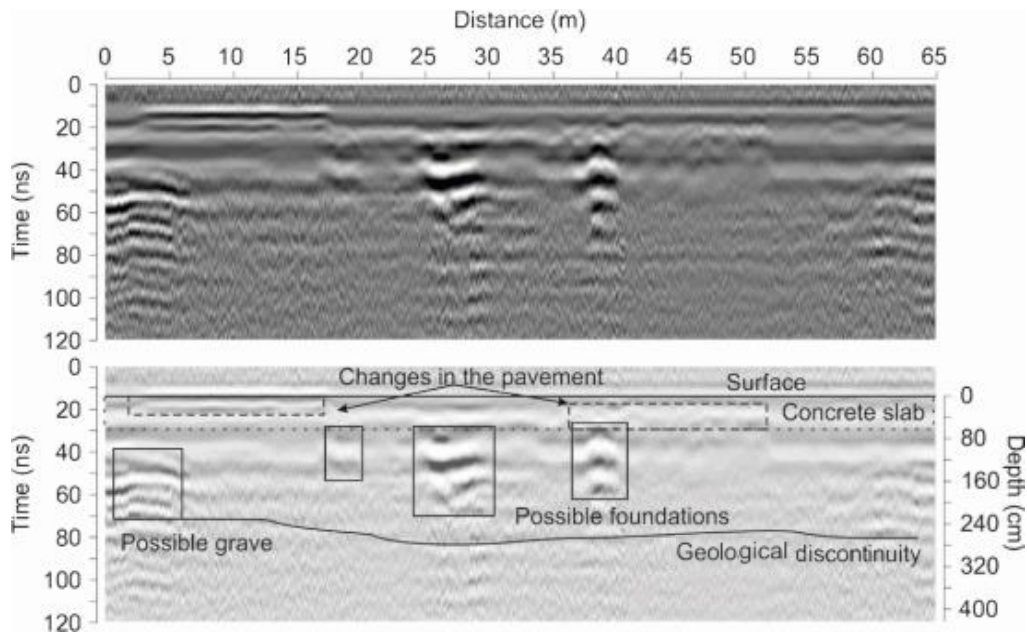


Figure 17: Subsurface anomalies below Santa Maria del Mar [32]

For individuals responsible for cemetery management, GPR is a practical, non-invasive way to identify the types of subsurface voids and anomalies that indicate unmarked graves without disrespecting cultural burial preferences, as shown in Figure 18. Additional applications of GPR within this context are forensic investigations where disturbing the surface risks destroying evidence and for clearing buried explosives from civilian areas.^{[33][34]}

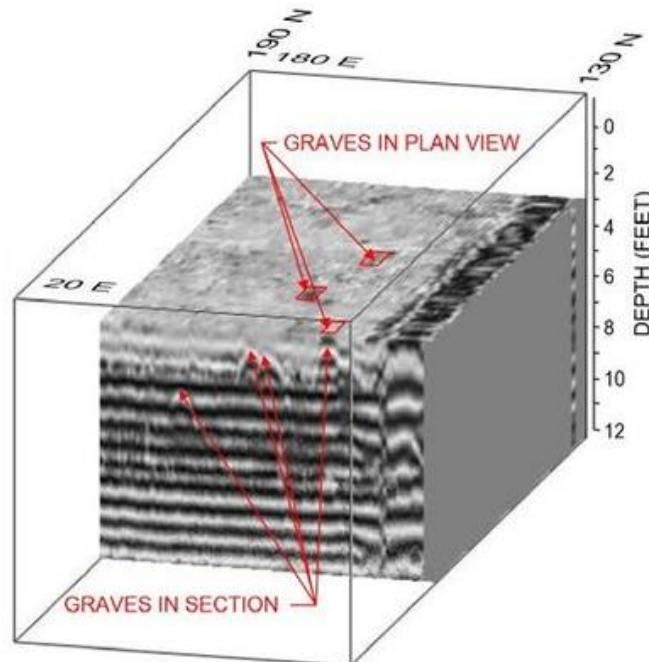


Figure 18: 3D scan of Beechwood Cemetery [35]

In an interview with a Public Works Director for a Georgia municipality, they shared the success of their experience working with GPR consultants to survey their historic cemetery. The goal of the survey was to locate the presumed 200 to 300 unmarked graves in the area, and instead ended up locating over 1,100.

LOCATING AND MAPPING UTILITIES, VOIDS, STORAGE TANKS, AND UNDERGROUND VAULTS

LOCATING UTILITIES

According to survey and interview data, local Georgia agencies are most interested in applying GPR to locate, determine the depth of, and map their utilities. Unlike traditional electromagnetic profiling and radio frequency pipe and cable locators, GPR is not limited to locating conductive (metallic) utilities. GPR is also unique in its ability to measure the depth of an object provided proper unit calibration. In addition to calculating depth, GPR can predict the type of utility located using a combination of material properties and estimated cable or pipe radii, as is shown in Figure 19. This ability is valuable to a municipality for design and construction planning, Subsurface Utility Engineering (SUE) quality levels, and right-of-way work.

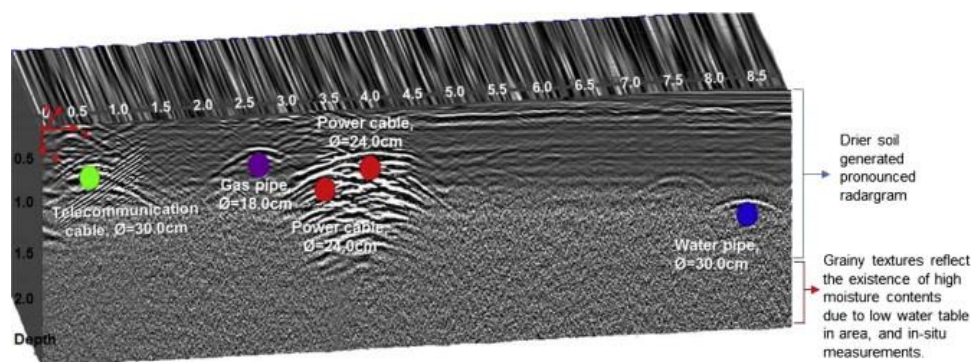


Figure 19: GPR detection of four utility types [36]

DESIGN AND CONSTRUCTION PLANNING

One Georgia municipality interviewed for the project spoke highly about the benefit GPR provided in waterline placement. For this work, GPR allows them to determine the ideal pipe placement to avoid conflict with water mains and know if the site can or cannot be designed around them. If not, they can relocate them before rather than during construction. GPR helps avoid construction delays and damage by better preparing the engineers and contractors to work around the existing infrastructure.

One Georgia municipality estimates they have had fewer than 5 incidents of damage due to mismarked utilities since they began using GPR for their work in 2008.

FINDING VOIDS

GPR can locate underground voids in natural and developed areas caused by sediment removal or collapse. If the soil above a void collapses, it will create a sinkhole risking severe damage to infrastructure. A 0.76 m deep void beneath a section of asphalt pavement is shown in Figure 20. The top layer of asphalt is not depressed, and the first sign of concern is the drop in the concrete base's reinforcement which would be otherwise undetectable without the GPR data.

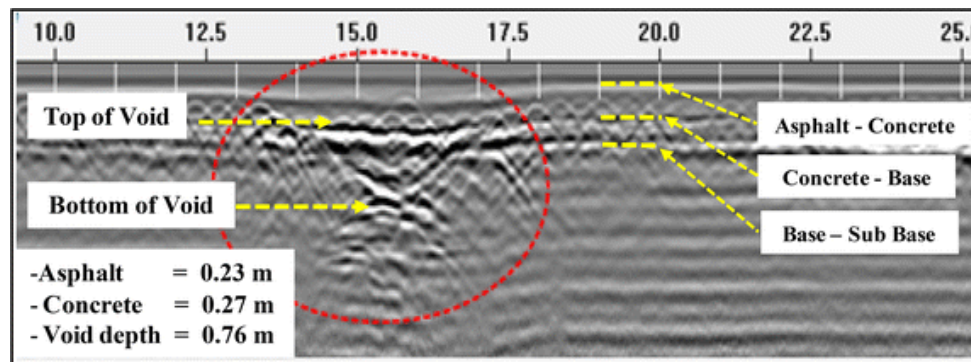


Figure 20: Void beneath asphalt pavement [37]

CONCRETE STRUCTURE (BRIDGES, DAMS, ETC.) INSPECTIONS

In addition to mapping underground objects, GPR's nondestructive nature means it can inspect embedded reinforcement and areas of concern in hardened concrete. In these scenarios, GPR replaces labor-intensive, potentially dangerous, and often inaccurate quality control methods.^[31]

LOCATING EMBEDDED REINFORCEMENT

Using GPR before cutting, coring, or breaking a concrete slab for new-build construction or renovation projects can prevent damage and delays. In slabs, GPR can identify subsurface objects like steel rebar, post-tensioned cables, pipes, and electrical wiring encased in conduits. This use can help determine the best spots for drilling into or

coring concrete sections and pavements. Figure 21 shows a radargram and depth slice of reinforced concrete.

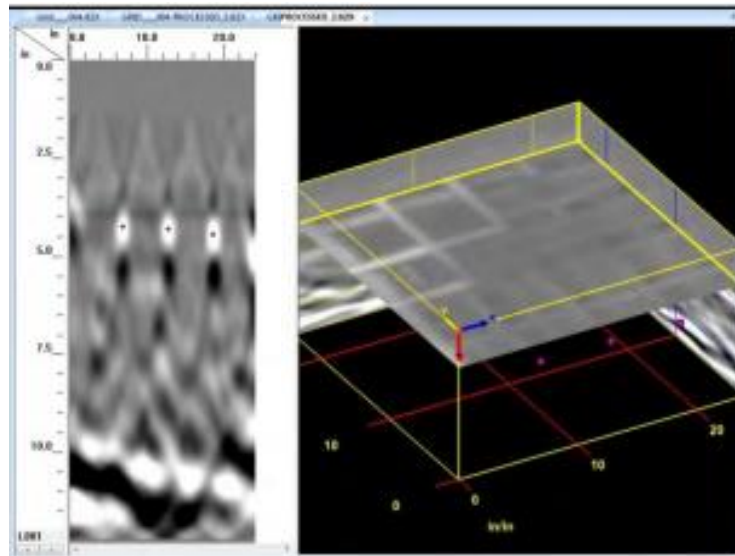


Figure 21: Radargram and depth slice of section of reinforced concrete [18]

STRUCTURAL CONCRETE INSPECTIONS

During precast concrete inspections, GPR can measure the cover depth, reinforcement location, and section thickness. However, the quality of results is lower for thick columns and members with dense steel mesh reinforcement where the signal cannot pass through.^[39]

ROADWAY AND PAVEMENTS

PAVEMENT ASSESSMENTS

As shown in Figure 22, GPR can identify layer interfaces, reinforcement, and slab joints in pavements. Provided proper calibration, it can measure layer thickness and monitor bridge deck deterioration and reinforcement corrosion. Pavement surveys can be performed using handheld, walk-behind, or driven units. Driven units are helpful when needing to scan large sections of a roadway as they can operate at the speed of traffic and prevent the need for traffic control measures. Locating and inspecting airport runways require a very high antenna frequency due to the large quantity and close spacing of reinforcement.

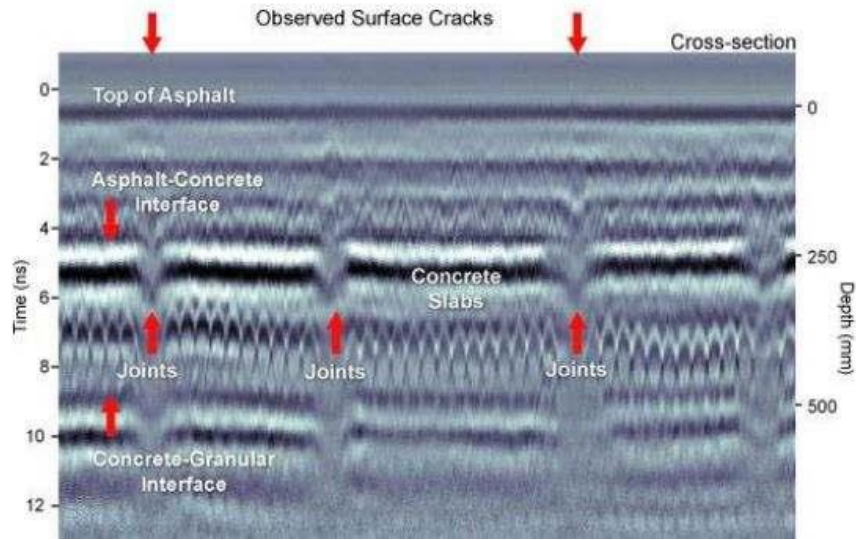


Figure 22: GPR image of pavement substructure [40]

GPR can assess pavement condition by identifying debonding (Figure 23), delamination, and cracking above and below the overlay. Additionally, it can determine the cause to be top-down or fatigue cracking from structural failure or an abnormality in the subgrade. Using GPR to survey roadways means that repairs to cracking and other pavement damage can be made before they are visible or a risk to drivers. Figure 20, from Chapter 3: “Finding Voids” is an example of how GPR can prevent problems due to unpredictable failures in the subgrade. Figure 24 shows the correlation between a section of pavement’s density of cracks to the depth of its reinforcement as measured by GPR. As is shown in the graph, the section with the most cracking has the deepest rebar.

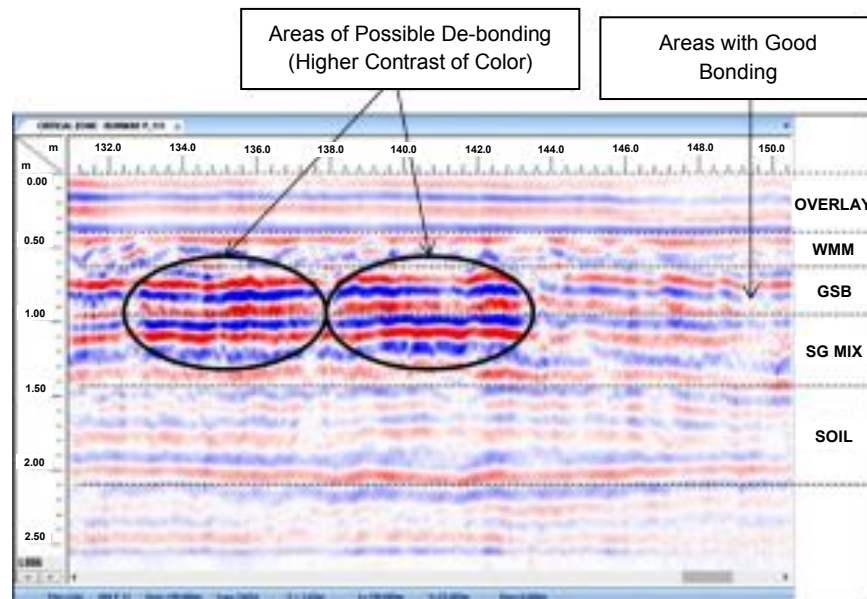


Figure 23: Airport pavement after excessive rainfall and flooding [41]

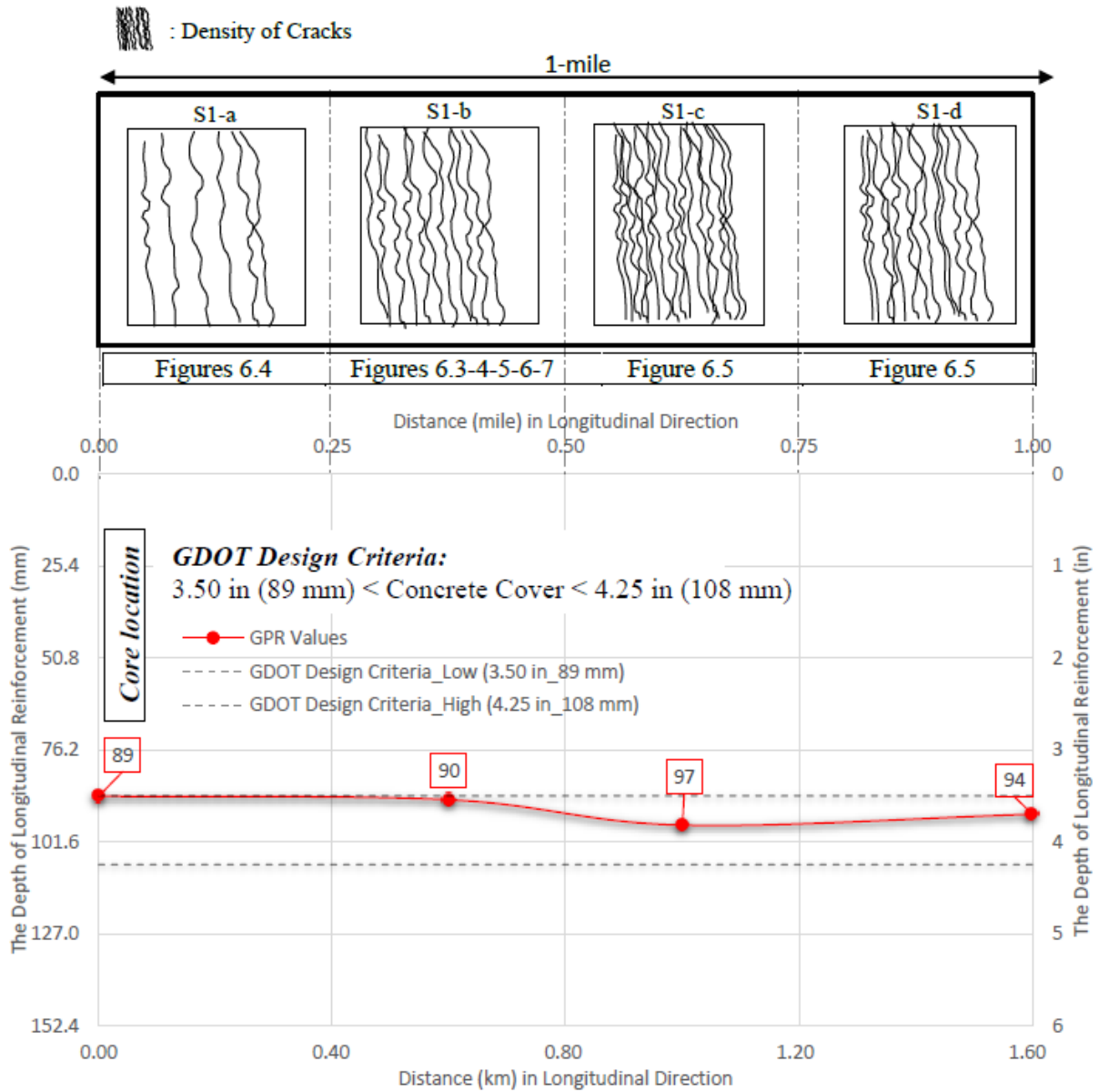


Figure 24: Density of pavement cracks compared to depth of reinforcement [42]

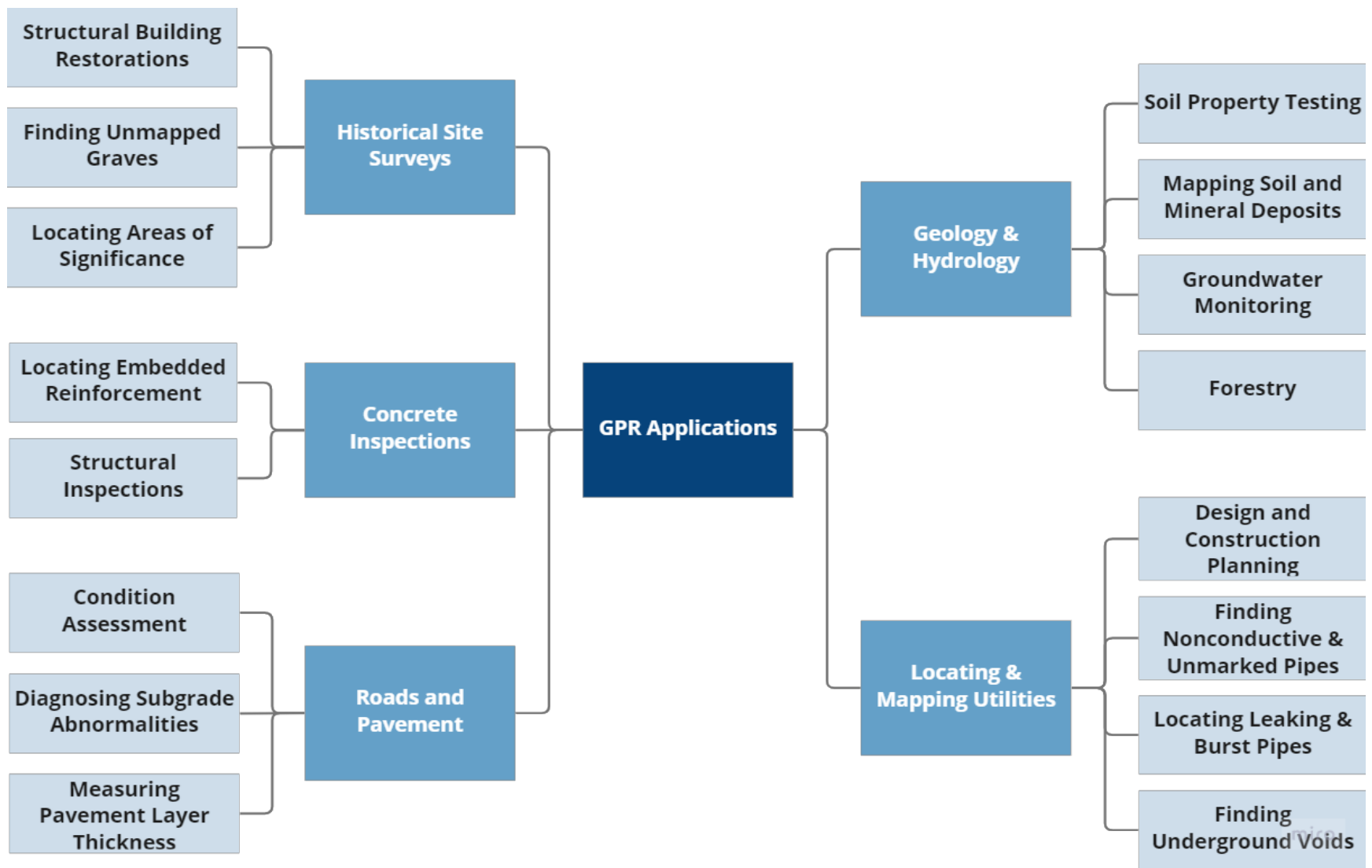


Figure 25: Common GPR Applications

CHAPTER 4: BEST PRACTICES AND DECISION MAKING

SELECTION OF IMPORTANT GPR ATTRIBUTES

The first choice after deciding to implement GPR is whether to conduct it in-house or to hire GPR consultants for the survey. If choosing to conduct the work in-house, the next step is determining the necessary unit type. The choice of antenna frequency will depend on the intended applications and affects the choice between units.

OWN VS. RENT VS. HIRE

The GPR procurement method decision matrix shown in Table 5 is based on industry recommendations and the experiences of Georgia municipalities. Departments with weekly, if not daily, locating needs that could benefit from GPR are more likely to own/rent than hire to save money and avoid being dependent on another company's schedule. Equipment rentals are available if users are interested in temporary access to GPR equipment or alternatives, like different antenna frequencies, for uncommon projects. Hired consultants can perform all of the tasks listed but those specifically marked "Hire Consultants" are unique due to the level of technical experience and equipment they require or legal liability concerns.

For example, consultants are useful when locating and mapping unmarked graves in a large cemetery. Compared to a municipality, consultants will have experience establishing survey grids, maintaining survey quality over multiple days, and will likely own multiple units and antennas to address the wide variety of potential subject matter. Consultants are not necessary for all large-scale projects, a city-wide survey of traffic control devices may be better and more cost-effective to do in-house. In that scenario, the subject matter is limited to known areas, has different material properties than its surrounding materials, and should not require as precise calibration as multi-day scans of the same landscape.

TYPES OF GPR UNITS

Three primary types of GPR units are typically used in applications related to municipal applications. The first, smallest type is handheld. These units are typically for concrete and vertical scanning. They are not limited to these applications, but for operator convenience and safety, they are not used to scan large areas or uneven surfaces. Walk-behind units are for applications requiring the traverse of smooth or rough surfaces.

These include utility locating, archaeology, and studying small sections of roadways. Vehicle-mounted units are for scanning pavements without requiring traffic control measures. Of the three, walk-behind units are the most versatile for municipal purposes, and depending on the manufacturer, there will be the option to include a GPS upgrade, a more rugged system, etc.

Table 3 provides a list of applications and the type of GPR unit typically used to perform them. Table 4 provides example pricing data for five different walk-behind GPR units. The year of purchase is included with the price, as well as the number of days of in-person training held by the manufacturer included in the purchase price.

Table 3: Selection of GPR Unit Type ^[2]			
	Handheld	Walk- Behind	Vehicle- Mounted
Survey Across Undeveloped Land		X	
Survey of Soil Properties		X	X
Scanning Beneath Developed Areas	X	X	
Locating Utilities Below Ground or Soils		X	
Locating Utilities Below Pavement		X	X
Survey of Structural or Reinforced Concrete Walls, Beams, Columns, and Shallow Floors	X		
Survey of Structural or Reinforced Concrete Floors and Foundations	X	X	
Survey of Pavement Section Properties		X	X
Surveying Pavement and Subgrade at High Speeds			X

Table 4: Example GPR Unit Pricing ^[2]					
Example Units:	1	2	3	4	5
Antenna Frequency (MHz)	250	250	600	250 & 700	400 & 800
Walk-behind	X	X	X	X	X
GPS Enabled	X	+\$5,000	+\$3,750	+\$1,284	X
CAD/GIS	X		X	X	X
Live Data Processing	X	X	X	X	X
Post Data Processing		X	X	X	X
3D Modeling		In-Post	Real-time	X	
Days of Training Included	One	Two	One	One	-
Price	\$18,000 (2018)	\$18,000 (2008)	\$21,260 (2023)	\$22,500 (2023)	\$15,550 (2023)

ANTENNA FREQUENCY SELECTION

The antenna frequency selection matrix included in Table 6 can be used to select the frequency(s) best suited for intended applications. The suggestions are not strict, and the influence of depth versus detail, object size, and effect of saturation discussed in Chapter 2: "Saturation" should be taken into consideration. For best practice, consult the references included in Chapter 6 or with a GPR expert or company. For a resource to help determine the types of units offering various antenna frequencies, see "GPR Parameters" in Chapter 6: "Survey Guidance." [2]

GPR Procurement Method Selection Matrix

Table 5: Suggested Method of GPR Procurement [2]

	Own or Rent & Operate	Hire Consultants
Preferences by Department		
Water & Sewer	X	
Utilities	X	
Transportation		X
Departments with a High Rate of Employee Turnover		X
Preferences by Task		
Anything Determining Legal Liability		X
Large Scale Cemetery Survey or Mapping		X
Extensive Locating Projects for Fiber Cable Installations, or Updating Traffic Control Records for GA HB1372	X	
Construction Project Management	X	
Improving the Level of SUE Investigation *	X	X
Determining Properties and Debris Content of Soils		X
Locating Voids in Developed Areas	X	
Daily or Frequent In-House Pipe & Asset Locating	X	
Burst or Leaking Pipe Locating	X	
Utility Locating & Mapping for GIS Documentation	X	
Locating When it is Unclear What May be Found **	X	X
Immediate Response Roadway and Right-of-Way Repairs	X	
Diagnosing Roadway/ Pavement Cracking ***	X	X
Locating Concrete Reinforcement	X	
Locating in or Beneath Densely Reinforced Concrete (e.g., Airport Pavement)		X

* Local agencies that frequently manage projects/ sites benefit from owning & operating a unit

** Well trained and experienced in-house locators may be comfortable doing this, but inexperienced may prefer to hire consultants to either run or interpret the survey

*** Pavement thickness scans are manageable, but understanding the subgrade soil properties may require specialized help

Antenna Frequency Selection Matrix

Table 6: GPR Antenna Frequency Applications ^{[2][9][10][43]}

Antenna Frequency (MHz)	2600	1600	1000	900	400	270	200	100
Approximate Depth Range	(0 – 1 ft)	(0 – 1.5ft)	(0 – 2 ft)	(0 – 3 ft)	(0 – 12ft)	(0 – 18ft)	(0 – 30ft)	(0 – 90ft)
Concrete Quality Control	X	X	X	X				
Structural Engineering	X	X	X	X				
Roadbed Subbase and Layer Analysis	X	X	X	X				
Forestry	X	X	X					
Archaeology				X	X	X	X	
Locating Utilities, Voids, and Storage Tanks				X	X	X	X	
Geology					X	X	X	X
Soil Exploration					X	X	X	X
Geotechnical Engineering						X	X	X

FUNDING

Funding the use of GPR, either through consultants or in-house, will depend on the department(s) interested in implementing it. It does pay for itself quickly, so utility departments interested in it may be able to partner with transportation or others who incur the cost and consequences of avoidable damage.

No special funding has been identified as an opportunity to pay for GPR units or consultants.

TRAINING

OPERATE IN-HOUSE

For those interested in operating in-house GPR units, it is crucial to recognize that training will be an ongoing process and that proficiency will take time and patience. The dedication needed to establish skills is why departments with high employee turnover rates are less inclined to implement the technology. Time to proficiency decreases as software becomes more sophisticated and systems more user-friendly. These improvements are seen in unit calibration requiring fewer manual data points and operator calculations, and automatic image adjustments.

MANUFACTURER OR GPR RETAILER:

Initial employee training will come from the manufacturer demonstration and training included with the purchase. The duration of these courses will depend on the manufacturer and, as reported, can last from one day to a week (see Table 4 for more information).

AVAILABLE RESOURCES:

Many resources for GPR training are available online, including free YouTube tutorials for data collection through data processing and interpretation. These do not allow the operator to ask the instructor questions but offer in-the-moment advice and solutions to common problems. In-person training courses are available through manufacturers, retailers, or GPR consulting firms.

Learning how best to calibrate units and estimate material properties will improve with time, but additional help could come from information sharing among Georgia Agencies. The values used for signal velocity through the subsurface material will influence the accuracy of the survey depth and clarity of the model, as well as how long it will take to calibrate units before use. Georgia has a diverse geological landscape, so building an agency-specific data set about each soil and rock type will take time and experience. A

way to expedite this process is to communicate with surrounding agencies that use GPR about their preferred starting values and strategies for surveying materials specific to the region.

CONSULTANTS:

In addition to conducting surveys, consultants (see Chapter 6 for more information) offer in-person and remote training opportunities. These can include new user training or opportunities for continuing education. In-person training can be held locally and specifically for your agency or as group workshops in a location of the provider's choice. Local in-person training workshops will usually require a minimum number of participants. If your agency cannot afford to pay for a team of employees to attend, coordinating with surrounding agencies to send their employees is a method to share the expense and establish relationships with other municipalities utilizing GPR. Coordinating training with other agencies is also a solution for small departments with few GPR operators.

CHAPTER 5: GETTING STARTED

STEP 1: EVALUATE NEEDS

Before hiring consultants or investing in a GPR unit, evaluate how beneficial or necessary the equipment is for the project(s) you have in mind and consider the following questions.

DOES IT MAKE SENSE TO USE GPR?

Is GPR capable of solving a problem that current equipment either cannot do or does less efficiently?

GPR is unlikely to improve asset management if the current approach is more functional or straightforward. However, if there are issues like frequent damage due to locating errors or old infrastructure lacking tracer wire, GPR is a productive, cost-saving tool. Using GPR to search for a 10-inch diameter box will use far fewer resources than excavating an entire area.

WHAT ARE THE PROJECT GOALS? ^[9]

Do you know what the survey is looking for?

Though it may sometimes be confirmation bias, it is easier to find what you're looking for than it will be to identify unpredictable features. Predicting the path of a sewer line between two storm drains, measuring depth to a mapped utility, or locating a vault within a perimeter, are more straightforward than identifying individual unrecorded objects.

Can the GPR results be confirmed using alternative testing methods?

Due to the challenges and potential for user error in a GPR scan, it is a good idea, if possible, to confirm the results with a second testing method. If scanning a section of pavement, taking a pavement core to compare with the GPR results at that point can help support or correct all of the GPR data if the problem is with calibration for material properties.

WILL GPR WORK AT THE SITE AND FOR THE PROJECT?

The Site:

Is the site clear of obstructions that would limit the maneuverability of a unit?

If there is dense ground cover in the area (shrubs, trees, etc.) it will make it difficult to traverse the intended site. Overall, the smoother the ground surface, the easier it is to scan and the clearer the results.

Is there signal interference at the site due to radio frequencies and wireless communication networks?

The scan will be influenced and negatively affected if there is significant signal interference from nearby cell phones, airports, or hospitals. Operators should put their phones on airplane mode and be aware of communication towers in the area.

How saturated is the area or subsurface? Is it fresh or seawater?

As is discussed in Section 2.3, the presence of water, particularly seawater, will change the signal velocity and attenuation and require a lower antenna frequency than the material would typically need.

Has the ground been disturbed recently?

Undisturbed, compacted soil will be better for scanning as the air pockets in disturbed soil complicate signal velocity.

The Project:

How likely is the antenna to pick up on the potential object(s) based on size, depth, and orientation?

The antenna will struggle to identify small objects that blend into the standard signal scattering caused by the subsurface material. Again, the smaller the target, the higher the antenna frequency needed. On its own, locating a small object is not a concern, but the deeper it is, the lower the required frequency, and the harder it will be to find. Lastly, orientation is a concern for the same reason as size. The larger the surface area of the target that the unit scans, the easier it is to identify. Perpendicularly crossing a pipe will be a smaller target than if the surveyor was walking in a line above it, and locating a horizontal pipe will be easier than a vertical pipe.

How different are the material properties of the subsurface compared to the object?

The more similar the electromagnetic properties, the harder it will be for the signal to clearly identify the point at which it crosses from the surroundings to the object.

Homogeneity is more of a concern when using GPR for archaeology or searching for things made of natural and local materials than for locating manufactured infrastructure.

IS OPERATING IN-HOUSE OR HIRING CONSULTANTS BETTER?

Is this project a routine occurrence? Or is it uncommon?

If the task calls for GPR and is a routine activity like locating pipes, it makes sense to invest in an in-house unit. If it calls for GPR but is a unique or complicated task like cemetery mapping, it makes sense to hire consultants rather than doing it in-house if inexperienced.

Is it more important to get quick or precise data?

One of the main benefits of owning and operating a GPR unit is the ability to employ it on your own schedule. Ownership can help in emergency situations and right-of-way locating by decreasing the time between identifying the need and receiving results. However, for surveys that require a high degree of precision, like situations involving legal liability disputes, quality is much more important than speed. By bringing in consultants, they will have more experience and sophisticated equipment and be liable for errors or misinterpreted data. Renting units is an option if you are interested in specialized equipment like car-mounted units for high-speed roadway surveys or need a different antenna for a short-term project.

STEP 2: SELECT A UNIT

Once you have identified your project needs and decided that implementing GPR will be beneficial, it is time to select the best unit for your work. When choosing system attributes, it is valuable to identify their potential short- and long-term applications. If the short-term plan is to apply it to measure pavement layer thicknesses, but the utility department would benefit from using it long-term, consider investing slightly more to get a dual antenna. This way it will be useful to both, and using combined funding will improve the quality of the units available to you.

Once there is a framework of budget parameters and intended applications, consider the attributes you need in a unit. Using information from manufacturers and the matrices in Chapter 4, compile what you need for antenna frequency(s), durability, data processing software, and continuing education and support. Knowing this will mean that when you request quotes and speak to retailers, you won't waste time considering equipment that does not meet your needs.

There is more to a unit than its antenna, so the variation in resources available to you based on the manufacturer should be considered, particularly if you do not have

experience with GPR. When making your choice, ask about the type and duration of training included with the purchase. In addition to the initial training, consider what kind of access there is to long-term support. Consider whether they offer services like unit calibration that extend the life of a system or if software upgrades are available to old units rather than limited to new systems. Access to instructional videos serves as an ongoing resource to operators and supports them long after the training included with the initial purchase.

Current municipal GPR operators recommend that when hosting a manufacturer unit demonstration, even if they tell you otherwise, take them to a site that has been excavated and mapped so that you can confirm the validity of the salesperson's scans. They may try to oversell the unit's abilities, and knowing the area well will prevent them from taking advantage of your experience level.

STEP 3: SECURE FUNDING

The next step after deciding to hire consultants or invest in a unit is to secure funding. Potential budget sources include but are not limited to, emergency repairs, utility or water & sewer department general funds, special council approval, user fees, or the municipality's general fund budget.

STEP 4: TRAINING

Training efforts will vary between municipalities and will be an ongoing effort. Training courses are available through GPR manufacturers, retailers, and consultants. Training can be held in-person or remotely and should be specific to the unit and brand in use.

When learning to operate a new unit or interpret scans, go to a site with known features due to a recent excavation and compare results. This will help with understanding how calibration affects the depth measurements, velocity properties of soils in the area, and how successful the antenna frequency will be at finding different sizes of objects and pipes.

STEP 5: IMPLEMENTATION

Once you are prepared to begin a survey, establish a data collection strategy. Planning how to approach the scan will make you less likely to run out of time or miss portions of the site. This step is the time to determine how best to use the antenna(s) available to you. If you had planned to use a high-frequency antenna, but it has rained overnight, and

the ground is now saturated, you will need to either use a different antenna, adjust your expectations, or delay the scan.

Next, you will need to calibrate your equipment. Note any perceivable changes in ground material and if there are any known subsurface objects in the area. If there are known objects, use them to calibrate for signal velocity, but otherwise, use the software available to you to estimate material properties.

STEP 6: DATA PROCESSING

Once the data is collected, there are three potential processing methods. Live data processing will occur on-site and in real-time. It will be less refined than post-processed but, depending on project needs, capable of providing accurate and productive data. The quality of live data, and whether it includes both 2D and 3D scans, will depend on the manufacturer and unit. Post-processing occurs after the survey and involves several extra steps to improve the quality of calculations and refine the imaging. Though the unit's manufacturer's recommendations are a good place to start, be careful not to rely on their automatic settings because over-filtering will remove objects it confuses for echo. The third method is hiring consultants to assist with data interpretation. The data quality based on scan accuracy is still important, but this can help in situations with uncommon or confusing results.

CHAPTER 6: EXTERNAL RESOURCES

ALL THINGS GPR

LEARNGPR / BIGMAN GEOPHYSICAL

LearnGPR is a GPR training and certification resource within Bigman Geophysical. Bigman Geophysical is local to Norcross, Georgia, and offers many GPR-related services. These include GPR project management, field support, data processing & analytics, equipment calibration & maintenance, and equipment for purchase or rent.

Bigman Geophysical: <https://bigmangeo.com/>

LearnGPR: <https://learngpr.thinkific.com/>

MANUFACTURER WEBSITES

Though they are made for marketing their products, many GPR manufacturers' websites offer valuable, detailed information about how GPR works, its applications and case studies, and other technical advice. Two example sites are given below.

GSSI: <https://www.geophysical.com/>

Sensors & Software: <https://www.sensoft.ca/>

REFERENCE TEXTS

BEGINNER

GPR BASICS: A HANDBOOK FOR GROUND PENETRATING RADAR USERS BY DANIEL P. BIGMAN

This is one of LearnGPR's GPR training resources and is useful for improving your GPR surveys as a new or experienced practitioner.

GROUND PENETRATING RADAR THEORY AND PRACTICE BY ERICA CARRICK UTSI

This is another "beginner's guide" to GPR. It is more technical than *GPR Basics* but offers important details to those more comfortable using and understanding the technology.

TECHNICAL

It is unlikely that these will be useful to an everyday practitioner, but to those interested in learning more, they are a good place to do so.

GROUND PENETRATING RADAR (2ND EDITION)

BY: DAVID J. DANIELS

This is considered the number one textbook on GPR and goes into more detail and technical specifics than beginner texts.

GROUND PENETRATING RADAR: PRINCIPLES, PROCEDURES AND APPLICATIONS

BY: A. PETER ANNAN

This is another key technical GPR text and also goes into more detail concerning the theory behind GPR science.

SURVEY GUIDANCE

GPR PARAMETERS

This is an online resource for helping plan and execute GPR surveys. Its resources include an automatic calculator for important parameters and survey requirements, information on what antennas are offered by various manufacturers, and a glossary of terms and equations.

Website: <https://gpr-parameters.ch/about.html>

MATERIAL PROPERTIES

WEB SOIL SURVEY

This is an online resource for finding the type of soil present at a project location. Its data can help determine what estimates of ground material properties should be used for calibration.

Website: <https://websoilsurvey.nrcs.usda.gov/app/>

APPENDIX A: ESTIMATED PHYSICAL AND MATERIAL PROPERTY VALUE TABLES

Table 7 is a method for quickly estimating the size of a wavelength in meters based on antenna frequency and the effect of a material's RDP.

Table 7: Estimated wavelength size in meters for various frequencies and RDP ^[9]

	100 (MHz)	200	300	400	500	600	700	800	900	1000
1 (RDP)	9.84 (ft)	4.92	3.28	2.46	1.97	1.64	1.41	1.25	1.08	0.98
2	6.56	3.28	2.20	1.64	1.31	1.08	0.95	0.82	0.72	0.66
4	4.92	2.46	1.64	1.25	0.98	0.82	0.69	0.62	0.56	0.49
6	3.94	1.97	1.31	0.98	0.79	0.66	0.56	0.49	0.44	0.39
9	3.28	1.64	1.08	0.82	0.66	0.56	0.46	0.43	0.36	0.33
10	3.12	1.57	1.05	0.79	0.62	0.52	0.46	0.39	0.36	0.33
15	2.53	1.28	0.85	0.62	0.49	0.43	0.36	0.33	0.30	0.26
30	1.80	0.92	0.59	0.46	0.36	0.30	0.26	0.23	0.20	0.20
40	1.64	0.82	0.56	0.43	0.33	0.26	0.23	0.20	0.20	0.16
75	1.15	0.59	0.39	0.30	0.23	0.20	0.16	0.13	0.13	0.13
81	1.08	0.56	0.36	0.26	0.23	0.20	0.16	0.13	0.13	0.10

Table 8 is the source of the example data used in Table 2.

Table 8: The approximate RDP, conductivity, & velocity of common materials ^[44] (Complete Table)			
Material	Relative Permittivity	Conductivity ($\mu\text{S}/\text{ft}$)	Average Velocity (ft/ns)
Air	1	0	0.9843
Ice	3-4	3.05	0.5250
Anhydrites	3-4	3.05 – 304.8	0.4265
Dry Sand	3-5	3.05	0.4922
Granite	4-6	3.05 – 304.8	0.4265
Limestone	4-8	152.4 – 609.6	0.3937
Shale	5-15	304.8 – 30,480	0.2953
Silts	5-30	304.8 – 30,480	0.2297
Saturated Sand	20-30	30.5 – 304.8	0.1969
Clays	5-40	609.6 – 304,800	0.1969
Freshwater	80-81	152.4	0.1083
Seawater	80-81	914,400	0.0328

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