Variation in information obtained from interpretation of ground penetrating radar (GPR) pavement investigation data

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ABSTRACT: Ground penetrating radar (GPR) data can be used to provide useful information about pavement structures. However, some limitations exist relating to GPR technology, and various limitations and uncertainties can exist in the reported information depending on the investigation methodology and the data analysis procedure used. The combination of all these factors results in a significant potential for uncertainty or variations in the analyzed data, and therefore consideration is required if the optimum amount of information from a GPR investigation is to be obtained. This paper discusses the possible errors and uncertainties that can arise from GPR investigations, and GPR pavement data is used to illustrate issues that can arise during data analysis and interpretation. Ways of minimizing and managing variations and uncertainties are discussed, and the use of appropriate data collection and analysis procedures are highlighted, so that the use of information from GPR can be optimized.

1 INTRODUCTION

1.1 *Ground penetrating radar (GPR)*

1.1.1 *Development*

The use of radio waves to indicate the presence of objects was initially developed in the first half of the 20th century, and by the early 1940's the now well-known acronym of "radar" (RAdio Detection And Ranging) was being used to describe the technique. However, despite some early ground penetrating applications, radar was predominantly used for airborne transmission and the first commercial systems for ground penetrating applications were not manufactured until the 1970's. Since these early ground penetrating radar (GPR) systems were manufactured, large developments in the use of radar for ground investigations have taken place, especially since the 1990's, including technological advances in the design of GPR hardware and software. Matthews (1998) summarises the use of radar for subsurface investigation and Olhoeft (2000) discusses the kind of information that can be obtained from GPR studies. The development of systems with greater processing power, smaller size of components, more user-friendly software and the ability to perform vehicle-towed surveys have contributed to the increased use of GPR in near surface ground investigations. Today, GPR is an accepted method for ground investigations of many kinds, and Daniels (2004) gives a comprehensive overview of the key elements of radar technology for ground investigation applications.

The developments of GPR technology have resulted in its adoption for road investigations. However, despite the increase in its use for this purpose over the past couple of decades, GPR (as with many other geophysical techniques) often remains under-utilised and its potential is often not fully realized. Some of the criticisms often directed at GPR investigations are that they don't provide either the accuracy of results hoped for or the type of information required. Reasons for this criticism can sometimes be related to an under-appreciation of exactly what GPR is capable of providing, but also the fact that several aspects of the GPR survey process contain the potential for uncertainties or variation. There is a tendency to attach more credence to investigation results obtained from more mechanistic testing methods (such as a core thickness, or a dynamic cone penetrometer test) despite the inherent uncertainties associated with such methods, than there is to have confidence in the results of GPR which is seen by many as a 'black box' technology. GPR investigations have a number of potential sources for uncertainty (as do all other ground investigation techniques), but a competently conducted GPR investigation can provide invaluable information to an engineer. By appreciating how and where uncertainties may arise, how these can be addressed, it is possible to obtain a fuller understanding of how GPR information can be used.

1.1.2 *Principles*

For most ground investigations, GPR systems operate by transmitting a radar pulse from an antenna into the ground, and recording the time taken for, and amplitude of, reflections of this pulse to be returned back to the antenna. The passage of radar waves through a material is dependent on the material type, condition, moisture content and pore fluid content. These material properties have an affect on what is known as the 'dielectric constant' of the material. The value of the dielectric constant is important because it relates to several parameters which are essential for the interpretation of GPR data, such as the velocity at which the radar waves will travel through the materials:

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

where V = velocity of radar wave through the material; c = velocity of light in free space (vacuum); and ε_r = dielectric constant.

When the materials in two layers in the ground have contrasting properties, some of the radar energy passing from one material to the other is reflected back from the material boundary to the antenna. The key to this process is for the materials to have different dielectric constants, and in practice most different road materials (bituminous, cement bound, un-bound aggregates, different soil types, etc) will have this contrast, although it should be noted that not all materials do. The amount of radar energy reflected will depend on the 'reflection coefficient' (which in turn depends on the contrast in dielectric properties of the materials) and is given by:

$$\rho = \frac{\left(\sqrt{\varepsilon_1}\right) - \left(\sqrt{\varepsilon_2}\right)}{\left(\sqrt{\varepsilon_1}\right) + \left(\sqrt{\varepsilon_2}\right)} \tag{2}$$

where ρ is the reflection coefficient, ε_1 is the dielectric constant of the upper material and ε_2 is the dielectric constant of the lower material.

GPR operates over a range of signal frequencies, but typically systems that operate between about 2000MHz (2GHz) at the highest, and about 400MHz at the lowest frequency, are used for engineering and 'shallow' investigations. As a general rule, a higher frequency of signal will give better resolution (i.e. more precise indication of depth), but a lower penetration (i.e. shallower maximum penetration depth). Conversely, a lower frequency will provide less precise depth resolution, but deeper depth penetration into the pavement.

Data from GPR survey lines are typically displayed as a 'pseudo-section', with distance along the horizontal axis and signal travel time (which may be converted to depth) on the vertical axis. The amplitude of the reflected signal (which indicates the presence of features and layers) is usually represented by a color- or grey-scale display.

1.2 *Use of GPR in pavement investigation*

In order to fully assess the condition of a road, information on its internal structure is required. Core samples or trial pits are often taken to obtain such information, and to confirm material types, condition and thickness. Whilst providing vital data, it is costly and time consuming to take cores (or excavate trial pits), and also has a further drawback that only data from the points where cores or trial pits are taken is obtained. Data for the sections of road between data points has to be interpolated.

The use of GPR allows information to be obtained concerning layer thicknesses, and other established uses include detection of construction changes, location of voids and wet patches (possible indications of poor support), location of reinforcement bars, location of excess sub-base moisture (indicating poor drainage), location of pipes and services and for indicating general material condition. All of these uses relate to the reflection of radar energy back to the antenna receiver, caused by a change in the nature of the material within the pavement structure. Whilst intrusive pavement investigations are still extremely useful (Mooney *et al* 2000) and are required for calibration of GPR data, the use of GPR allows the amount of intrusive investigations and amount of time taken for surveys to be reduced, and the amount of information obtained about the pavement to be increased.

Using the data from a GPR investigation allows a continuous record of data to be collected along the entire pavement length, reducing the overall risk and uncertainty which can result from the use of pavement investigation techniques which obtain data only at discrete points. GPR data can be analyzed in several ways to obtain information about several parameters, and guidelines on its use pavement investigation have been incorporated into several 'official' documents such as the UK Design Manual for Roads and Bridges (DMRB). One of the main uses described in the DMRB, and possibly the most common use of GPR when planning maintenance of roads, is to provide pavement layer thickness values. Such values can be used as part of the back-calculation of stiffness values from falling weight deflectometer (FWD) surveys. The FWD measures deflections caused by impact loading of the pavements surface, and these data can be used to calculate the stiffness of pavement layers – as long as the thickness of the layers is known. Traditionally coring at discrete points would be used, but the use of GPR to determine thickness allows more accurate and confident determination of layer thicknesses values, allowing a more confident prediction of layer stiffness which in turn provides improved assessment of the maintenance requirements for the pavement.

2 LIMITATIONS AND UNCERTAINITES

2.1 *Introduction*

All pavement investigation methods will carry certain limitations and uncertainties, from various sources, in the information that can be obtained. The sources of uncertainty or limitation that effect GPR information can be categorized into three areas:

- Technological and scientific issues
- In-situ investigation methodology
- Data analysis methodology

Sources of potential uncertainty are identified and outlined below, particularly those arising during the analysis of GPR data. Through identification, investigation and discussion of the factors which may result in uncertainty and variation in GPR data interpretation, it is hoped that the effect of such factors can be understood, managed and minimized.

Work has been previously conducted to try and assess the certainty to which GPR can provide data and information, and various quantifications on the levels of accuracy that can be achieved have been reported. Saarenketo & Scullion (2000) summarize a series of investigations which reported depth accuracies of 3-5% from GPR data which had not been calibrated with cores (which is the least accurate way of estimating depths) and Willet & Rister (2002) report some instances of depth errors of core calibrated GPR data of less than 1%. However, determination of uncertainty or error in GPR depths may often be undertaken under 'ideal' or artificial conditions, which sometimes may not take into account non-technical factors. Generally the actual uncertainty in GPR depths may be affected by more parameters than are taken into consideration during research studies.

Guidance in DMRB states that "10 % level of accuracy can generally be achieved for layers greater than 75mm thick" and that "6 % level of accuracy can be achieved for layers greater than 125mm thick". However, this should not be taken as an absolute guide to the accuracy that GPR can determine layer thicknesses. The DMRB values give an indication of overall accuracy, but the sources for potential inaccuracies are many and varied, and each source of potential error has to be considered and managed in order to produce the most useful and appropriate information for the pavement engineer.

Studies reporting the values for the accuracy of GPR determined layer thicknesses are useful, but such values are often determined by a quantification of the agreement between GPR data and ground truth data. Not only does this assume that the locations of ground truth data has been precisely and accurately recorded onto the GPR data record (something which may not always be the case during a pavement investigation) but it also only provides a determination of one aspect of the overall uncertainty which may be present, and which is largely based on the scientific limitations of radar technology. It can be more difficult to determine a value of error or uncertainty which may have arisen from sources such as the data collection methodology or from the data analysis and processing procedures. Whilst it is sometimes difficult to state a quantitative value for some of the uncertainties in data, it is important to be aware of their sources and understand their significance so that their impact on the quality of output from a GPR investigation can be minimized.

2.2 *Significance of variation in GPR information*

Variation or uncertainties in GPR information results in a degree of risk to the pavement engineer using the information for design or planning. As mentioned above, there are a number of features and properties of pavement that can be identified by GPR, but one of the main uses of GPR data in pavement engineering is to determine layer thicknesses and identify changes in construction, for input into analysis of pavement condition for maintenance assessment. Such analysis typically takes the form of inputting GPR determined layer thickness values into the back-analysis of FWD data, and the use of GPR in this way is becoming a more common practice. When used effectively it can achieve a higher level of accuracy than with the use of coring information alone, but if used incorrectly it is possible that the GPR data will be less accurate and in the worst cases, may even provide an incorrect interpretation of the pavement condition.

The level of accuracy for GPR in determining layer thicknesses has been investigated by a number of previous studies, and a value of 6% (stated above, from the DMRB) is reasonable for routine or non-research investigations. Other research, also mentioned in the DMRB, has found that an under-estimation of 15% in thickness can lead to an over-estimation of 50% in layer stiffness. So, the implication is that the back-calculated stiffness may often be up to 20% out from the true value. Pavement material stiffness errors of this degree could lead to over- or under-design of maintenance treatments, and consequently incur un-necessary associated costs. Hence, the ability to reduce and minimize errors and uncertainties in layer thickness information is of great importance to the pavement engineer.

Due to the increased confidence in core location referencing that is achieved during slower speed surveys (discussed below), performing GPR investigations in this way may be the most appropriate method for use where data is used for pavement stiffness analysis. Clearly a requirement is that adequate core information is also needed to achieve this. Also, some back-analysis software packages are able to use individual construction thicknesses for each FWD test point, which can dramatically increase the level of accuracy. Again, there is a proviso that accurate locational referencing is used and that each thickness used is representative of the actual depth present.

The importance of accurate GPR determined thickness data, for use in back-calculation of stiffness values, has been discussed above because it is probably the most common current use of routine GPR pavement investigation data. However, it is not of course only when GPR information is used for this purpose that minimizing uncertainty or variation is important. All other applications of GPR investigations (mentioned in Section 1.2) all carry their own risks which are increased if the uncertainty in GPR data is not managed correctly.

2.3 *Sources of variation in GPR information*

2.3.1 *Overview*

For a given pavement structure, there can be variations in information obtained depending on how a GPR investigation is conducted, and how the GPR data is analyzed. Also, there are some known limitations relating to GPR technology that need to be managed, regardless of how the investigation is conducted and how the data is analyzed. The following summarizes the potential sources of errors in reported information from GPR investigations.

The quality of GPR data obtained from a survey is a function of several factors, including the dielectric properties of the materials and other site specific material conditions as discussed below. Also, the GPR system used on site (antennae type and power, gains used for data collection, survey methodology) will affect the data quality. The amount of information which can be obtained from the data is affected by the processing and analysis procedure used (software, processing procedures performed, data presentation method, etc). The competence of the GPR operator and data analyst can also affect the results obtained. Many of these factors can be addressed to optimize data and information quality, but it should be noted that some factors are less controllable.

2.3.2 *Technological limitations of radar*

Many of the limitations of early GPR systems, such as low sampling rates and poor memory capacity have been overcome with developments in electronic and computing technology. However, there are several issues which are not so easily overcome. The passage of a radar signal pulse is governed by the physical laws concerning electromagnetic waves, and the use of GPR data relies on recording the reflections of electromagnetic waves transmitted into the pavement structure. The different types of electromagnetic wave are characterized by their frequency. The frequency and speed of the waves will determine their wavelength, and the wavelength of the material will have a large effect on both the penetration depth of the signal, and the resolution (or precision) to which depths can be determined. This phenomenon, where higher frequency signals have greater resolution but lower penetration than lower frequency signals, is a physical limitation of GPR technology, and has to be taken into account when planning the GPR collection methodology (see 2.3.2).

There are also certain pavement and soil conditions that can have an affect on the quality of GPR data which can be obtained, such as materials with high moisture contents (although the ability of GPR to determine areas of higher moisture is, in itself, a useful ability), highly conductive materials (which attenuate the radar signal), and reinforcement in pavement layers masking deeper features. Therefore, the presence of such features in a pavement sometimes may limit the information that can be obtained. However, when the presence of such conditions are expected and recognized in survey results, GPR can still provide useful pavement investigation data (Barnes & Trottier, 2002).

Sometimes, features of the pavement will affect the efficiency of GPR in distinguishing details. For example, signal reflections from disintegrated material boundaries can prove difficult to accurately map on a GPR pseudo-section, causing uncertainty in the identification of distinct boundaries between materials. However, this problem is not just restricted to GPR data – core and other intrusive data are also liable to uncertainty when identifying depths of disintegrated material. The ability of the GPR data analyst can sometimes assist in data interpretation in such cases (see 2.3.3).

As stated in Section 1.1.2, the dielectric constant of a material is of great importance in GPR work. Several properties of materials have been shown to influence the dielectric constant including the temperature, moisture, pore fluids, porosity, density, mineralogy, geometries, and electrochemical interactions (Martinez et al, 2001 & Jaselskis et al, 2003). Generally, a given pavement material will have a range of values for its dielectric constant, because of such variations in the specific properties of that material. For example, Daniels (2004) reports the typical ranges of dielectric constant values for “dry asphalt” to be 2-4, “wet asphalt” to be 6-10, “dry concrete” to be 4-10 and “wet concrete” to be 10-20. Hence, a (dielectric) contrast between different materials may not always be the case, and the resulting low reflection coefficient may mean that resolution of material boundaries is not possible. Again, these physical limitations of GPR technology can sometimes be countered by employing the appropriate on-site data collection methodology (see 2.3.2). However, there will always be some situations where the physical site conditions mean that, even if every other aspect of the GPR investigation is conducted to the highest standard, the GPR data acquired can not adequately identify features or resolve layer boundaries.

2.3.3 *In-situ investigation procedures*

The methodology used to collect GPR data should be tailored to the specific site under investigation. It is not possible to provide a single methodology which will always provide the optimum data collection procedures at all sites. However, it is possible to outline general guidelines to minimize the limitations and uncertainties which may arise from the way data is collected and from the specific nature of the site. Also it is possible to use the data collection methodology to address some of the issues arising from the nature of GPR technology (see above).

Consideration of the site materials and depth of interest should be made so that the appropriate frequency of antenna(s) can be used. Often the use of several antennas, providing a range of radar frequencies, provides the best coverage of depth penetration and resolution. Another factor, which can be addressed with appropriate on-site methodology, is to ensure that a sufficient density of data is obtained along the survey profile. Where detailed information is required a sufficiently high number of pulses (samples) per meter should be taken along the survey line, which may require a slow speed survey along the highway. This increases the time taken for the survey, but reduces the risk of obtaining insufficient density of data for the interpretation required. In locations where less detail is needed, less pulses per meter can be taken allowing a higher speed survey to be performed. A similar issue is the consideration of how many survey runs to perform. Depending on the requirements of a project, a single run along the pavement surface may be sufficient, but sometimes several runs along the pavement (e.g. in both wheel-tracks of a highway lane), or the inclusion of transverse runs may be required to minimize the risk of missing significant features.

There are several ways to calibrate GPR data (i.e. convert the signal reflection travel times recorded on site into depths, during analysis), but the most accurate method is to correlate the data with intrusive surveys. Intrusive surveys (usually in the form of cores, but also trial pits) are used to calibrate GPR data to a suitable level of accuracy, and the number of intrusive investigations will depend on the nature and homogeneity of the site materials. Targeting core locations after or during the GPR survey can assist with this process, and it is imperative that accurate marking of site locations in relation to GPR data points is conducted, not only to reduce uncertainty in core calibrations but also to ensure accurate reporting of the GPR data at the correct location on the site. Most GPR systems allow core locations to be marked directly on the GPR data pseudo-section, but in any case special attention should be paid to a sensible and easy to follow site chainage system, marked from fixed locations on site.

All of the above should be considered individually bearing in mind the specific nature of the site under investigations, and a dialogue between all members of the investigations team should be maintained to focus the information provided by the investigation on the needs of the end user.

2.3.4 *Analysis procedures*

GPR data processing and interpretation is not a fixed process, and there is a large range of processing steps that can be applied in order to obtain useful information from the data. The nature of the site, the quality of data obtained, and the required use of the data will effect which specific processing steps are required. Some stages of GPR data processing and interpretation have little potential to create variation between different analysts, as they are stages which apply procedures (for example, background noise filtering) to the entire GPR data set. However, one analyst may have a different preference or opinion on which of the various available procedures are relevant. For pavement investigations which focus mainly on layer depth determination, it is the processing stages which depend more on the experience, competency and preferences of the analyst which will have the greater effect on information variation between different analysts.

When core calibration is performed, often several cores are used within the same GPR data file (i.e. within the same survey run) for calibration. The use of several cores can result in different calibration velocities for each core. Where this is the case, sometimes an average velocity is used to convert signal travel times to depths, and other times it may be possible that, for example, several cores produce very similar velocities and a single core is in disagreement with the others. Also there can be instances where a core sample shows signs of deterioration or uncertainty in depth values for some reason, and the confidence attached to that core my be lower than other cores. Slight changes in materials can also affect velocities calculated from generically similar core materials. In such situations, the analyst has the main input into what value of calibration velocity is actually used. Variations in expertise, background and experience mean that, as with many engineering issues, there can be differences in professional judgment.

It is more difficult to quantitatively assess the uncertainties that may arise from the input of the data analyst, than those from technological or methodological issues. Ultimately the data analyst responsible for processing and analysis of the GPR data, in conjunction with other pavement data, provides the interpretation of what the GPR data shows, and it is this interpretation which is passed on to the end-user of the information (client, engineer, planner, etc).

As mentioned above, the production of useful pavement information, such as layer depths or areas of excess moisture, from GPR data requires a number of data processing and analysis stages. Some of these stages require the input of the analysts own geophysical and engineering knowledge in a qualitative way, as features within the GPR data are identified and reported to the end-user who is not likely to be a GPR specialist. A discussion of issues relating to the provision of useful information through analysis and interpretation of investigation data is given by Evans (2003).

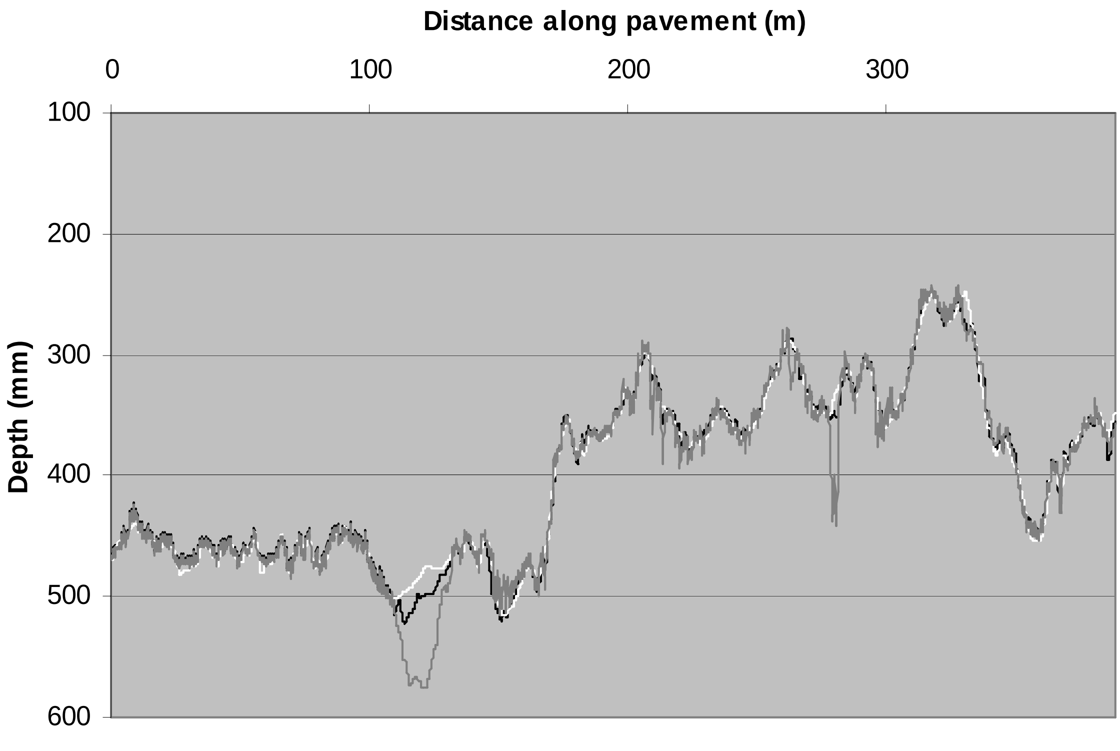

Figure 1. GPR data showing depth to bottom of bituminous pavement layer: three interpretations of the same raw data-set.

Figure 1 shows processed GPR pavement investigation from a 400m length of motorway, in the UK. The white, black and grey lines indicate the depth to the bottom of the bituminous pavement layer, each line having been determined by a different analyst from the same initial raw data-set. The information presented (depth to the bottom of the bituminous material) is just one set of information that GPR data can be used to provide, and the data used was of good quality and had confident core calibration. As can be seen in Figure 1, the three interpretations of the same set of raw GPR data are broadly in agreement. However, despite the high quality raw data used, there are still several places where the analysts individual judgment and input have affected the analysis procedure and resulted in variations in interpretation (e.g. at distances of approximately 120m and 280m).

When considering variations from analyst input, unless the entire pavement under investigation is excavated and carefully measured, there can be no confirmation of 'right' and 'wrong' answers. However, the ability of an analyst to accurately interpret data will be enhanced and the risk of misinterpretation reduced through adequate training and experience in aspects of pavement engineering and GPR principles and technology.

3 CONCLUSIONS

GPR provides one of the most useful tools available to the pavement engineer. Information on a variety of parameters can be obtained, including layer depths, construction changes, material condition, location of features such as steel-work and pipes/services, areas of excess moisture and voiding. However, despite much recent development over the past few years, the various uncertainties that are associated with GPR investigation data have often resulted in its under use and under appreciation as a pavement investigation technique.

If the various uncertainties and sources of variability in GPR data are considered, it may be possible to indicate a 'confidence level' or other quantification of accuracy in the reported information (particularly for the less qualitative factors). Such a quantification of the quality of information is often not performed for some pavement investigation techniques. This can lead to a misconception that precise values reported for some investigations (for example, a thickness measurement from a core log, a stiffness value derived from an FWD test or a density value from a laboratory test), given without any quantification of accuracy or uncertainty, reflect high accuracy in the data. However, each individual pavement investigation method will have its own uncertainty or degree of variability associated with the data. The accuracy and confidence from GPR data can often be greater than that obtained from other investigations, especially when the technology and procedures used during GPR investigations is understood and appreciated.

GPR relies on both science and 'art', the interpretation of information in both quantitative and a qualitative ways. The optimization of on site data collection methodology can be used to address several technological issues, and the methodology employed will have a large influence over the overall ability to extract useful engineering information from GPR data. Also, individual analyst opinion or preference can influence the information output that results from processing and analysis of GPR data (as with other pavement investigation techniques). Whilst some GPR data processing options are fixed in their nature, some of the input of a GPR data analyst is qualitative and based on a combination of the individuals skill, training, experience and knowledge of both ground radar and pavements.

This paper has outlined the sources of GPR data uncertainty and variation, and described how these issues can be addressed and managed. Such sources can include technological limitations, uncertainties associated with the data collection methodology and variations arising from the procedures used to analyze data. By discussing and outlining the issues relating to these three areas of potential uncertainty and variation, it is hoped that both practitioner and engineers will have an enhanced understanding of how best to obtain and use information from GPR.

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