Optimising the use of ground penetrating radar (GPR) for urban road investigations

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Abstract: Although ground penetrating radar (GPR) technology has existed for many decades, it has only been in the last 15 - 20 years that it has undergone the critical development facilitating use in surface ground investigations. GPR is now a commonly used geophysical technique for assessing layer thicknesses and material condition of road structures and foundations.

Assessing the condition of road structures, foundations and the supporting ground, to plan subsequent maintenance, is essential to allow the efficient long-term functioning of an urban transport network. Intrusive investigations provide vital information, but are often costly and time consuming, and also have the limitation that only data at discrete points is obtained.

The nature of urban sites means that the ground conditions are often highly variable. Existing road structures have often been subject to much maintenance and re-construction, and many urban roads are constructed over ground that has had a previous use. This can result in roads and their foundations containing several layers and sections of material of different ages and condition, often overlying discrete buried objects or structures. Also, it is common for urban sites to contain buried service pipes of various materials and purpose.

Various other un-controllable site specific parameters can affect the quality of GPR data obtainable, including road and ground material type and moisture condition, but it is possible to design a GPR survey to obtain the optimum data from a site by adjusting factors relating to the in-situ investigation methodology.

Using examples of recent urban road investigations, this paper outlines how the whole process of GPR investigation has to be carefully managed from the planning stage, through the site investigation methodology, to the data processing and presentation, to ensure optimum benefit to the end user.

Résumé: Bien que la technologie pénétrante au sol du radar (GPR) ait existé pendant beaucoup de décennies, elle a seulement eu lieu en 15 - 20 dernières années qu'elle a subi le grand développement pour l'usage dans des investigations proches de terre surface. GPR est maintenant une technique géophysique généralement utilisée pour évaluer des épaisseurs de couche et l'état matériel des structures et des bases de route. Évaluant l'état des structures de route, les bases et la terre de support, pour projeter l'entretien suivant, est essentielle pour permettre le fonctionnement à long terme efficace d'un réseau urbain de transport. Les investigations intrusives fournissent des informations essentielles, mais prennent souvent coûteuses et du temps, et ont également la limitation que seulement des données aux points discrets sont obtenues.

La nature des emplacements urbains signifie que les conditions au sol sont souvent fortement variables. Les structures existantes de route ont souvent été sujettes à beaucoup d'entretien et de reconstruction, et beaucoup de routes urbaines sont construites au-dessus de la terre qui a eu une utilisation précédente. Ceci peut avoir comme conséquence les routes et leurs bases contenant plusieurs couches et sections de matériel des âges et d'état différents, les objets ou les structures enterrés discrets souvent sus-jacents. En outre, il est commun pour que les emplacements urbains contiennent les conduites d'alimentation enterrées de divers matériaux et but.

Les paramètres spécifiques de divers autres emplacement incontrôlable peuvent affecter la qualité des données de GPR procurables, y compris l'état matériel de route et de type et d'humidité de la terre, mais il est possible de travailler une enquête de GPR pour obtenir les données optimas d'un emplacement en ajustant des facteurs concernant la méthodologie in-situ de recherche. L'utilisation des exemples des investigations urbaines récentes de route, des contours de cet article comment le processus entier de la recherche de GPR doit être soigneusement contrôlé de l'étape de planification, par la méthodologie de recherche d'emplacement, à l'informatique et à la présentation, pour assurer l'avantage optimum à l'utilisateur d'information a obtenu.

Keywords: Geophysics, highways, in situ tests, site investigation, data analysis

INTRODUCTION

"Transport is Civilization" was the motto of an organisation that controlled the planet, in one of Rudyard Kipling's stories (Kipling 1905). Whether such an organisation will ever exist is debateable, but it can be argued that its motto holds true. Almost all aspects of society can be influenced by transportation. Roads, as a major transportation mode, have been one of the most important factors in the development of the modern world, and remain a vital aspect for the efficient functioning of most cities around the globe.

Many issues exist (outside the scope of this paper) relating to urban transport, and a co-ordinated approach is required to address the current problems associated with transportation. Urban roads being prone to congestion, causing increased pollution from vehicle exhausts, disruption and increased travel times, are one of the aspects of a modern transport network that require maximum efficiency if an integrated transport network, and sustainable mobility, is to be achieved. Assessing the condition of urban road structures, to plan subsequent maintenance, is essential for the long-term functioning of a road network. Optimising the methods used for such assessment will lead to better information about the road and its underlying ground conditions. The condition of urban road structures is affected by a number of factors including: the properties of the road pavement, the supporting sub-base and the subgrade (natural ground), and the ability to obtain good information about the entire road structure, from pavement to subgrade, allowing appropriate maintenance programs to be planned.

Several methods are available to investigate road structures non-intrusively, and with minimal damage or disturbance of the structure. It is common practice to implement some form of routine investigation of road structures, and to use the data from these investigations to target more detailed structural investigations. Ground penetrating radar (GPR) is becoming one of the main methods of providing information on road structural condition to the highway engineer. The use of GPR for urban road investigation merits special consideration due to the often highly variable and complex nature of the road structure and underlying ground encountered in urban environments. Pavements, sub-bases and the subgrade/natural ground often contain different materials with different properties in relatively close proximity.

This paper outlines the development and principles of GPR as applied to urban highways, the nature of non-motorway urban roads and the specific issues related to their in-situ investigation, and then goes on to detail how the on-site methodology for GPR surveys can be optimised for (non-motorway) urban road investigation, using examples of successes and limitations of actual investigations to illustrate key points. The site investigation process for the road structure (i.e. pavement, sub-base and subgrade/natural ground) is considered, from the planning stage before any site work is undertaken through data collection and analysis to presentation of information to the end-user.

GROUND PENETRATING RADAR (GPR)

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 have to be interpolated. In the past 15 years or so, the use of GPR (which transmits and records the passage of electromagnetic waves through the pavement structure) has become more widespread, for the determination of layer thicknesses and to provide information on the general material condition, presence of voids, reinforcement and other discrete objects of interest for entire pavement sections. Intrusive pavement investigations are still extremely useful (Mooney *et al* 2000), and are required for calibration of GPR data, however the number of intrusive investigations and the time taken for surveys can be reduced, and the amount of information obtained increased, by the use of GPR.

Development

Today, GPR is an accepted method for a wide variety of ground investigations, for example, Daniels (2004) comprehensively reviews the key elements of radar technology for sub-surface applications. Radar technology was initially developed in the first half of the 20th century, but the first commercial systems for ground penetrating applications were not manufactured until the 1970's. The majority of the developments in the use of radar for ground investigations, including technological advances in the design of GPR hardware and software, have taken place since the 1990's. 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 features such as 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. This has assisted in the adoption of GPR for road investigations, reflected by its specification in guidance documents such as the UK Design Manual for Roads and Bridges (DMRB). However, despite the increase in its use over the past couple of decades, GPR (as with many other geophysical techniques) often remains under-utilised and its potential is not fully realised in many engineering and geological applications.

Despite this recent development, there are several issues to be aware of when considering the use of GPR, as illustrated in studies published on various aspects of the accuracy and applicability of GPR for pavement and ground investigations. There are certain pavement and soil conditions that may have a detrimental affect on the quality of GPR data, materials with high moisture contents, highly conductive materials, and reinforcement in pavement layers masking deeper features, for example. However, when the presence of such conditions are expected and recognised in survey results, GPR data still provides a useful tool for pavement investigation (Barnes & Trottier 2002).

Principles

For ground investigations, GPR systems operate by transmitting a radar pulse from an antenna into the ground, and recording the time taken for reflections of this pulse to be returned back to the antenna. The passage of radar waves through a material is dependent on its dielectric constant and electrical resistivity, which are in turn controlled by material type and condition, moisture content and the ionic content of pore fluids, for example. These material properties have an affect on the dielectric constant of the material, which governs how fast a radar signal travels through a material. When the materials in two layers in the ground have contrasting properties, a fraction 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

$$\rho = [\,(\sqrt{\varepsilon_1}) - (\sqrt{\varepsilon_2})\,] \,/\, [\,(\sqrt{\varepsilon_1}) + (\sqrt{\varepsilon_2})\,]$$

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 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. This type of radar data display indicates the amplitude of the reflected signal in colours or greyscale. In the example shown in Figure 1, white and black indicate a strong signal reflection (i.e. an indication of a material interface).

Limitations

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 mentioned above. 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, see Figure 1). The competence of the GPR operator and data analyst can also affect the results obtained. Many of these factors can be addressed to optimise data and information quality, but it should be noted that some factors are less controllable. Generally, in-service materials have a range of values for their dielectric constant, so a (dielectric) contrast between different materials will not always be the case, and the resulting low reflection coefficient may mean that resolution of material boundaries is not possible. Also, as mentioned above, wet material tends to absorb and attenuate GPR signals more, meaning less energy is reflected back to the antenna, resulting in lower quality resolution of GPR data being obtained on site. Disintegrated material boundaries can also prove difficult to accurately map on a GPR pseudo-sections. These factors can cause uncertainty in the identification of distinct boundaries between materials. 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.

Modern use of GPR

The guidance in the DMRB states the current recommended uses of GPR in pavement investigations, including use of both air-coupled and ground-coupled antennae. The main 'standard' use of GPR, especially for integration with falling weight deflectometer (FWD) data to produce stiffness values for individual layers, is to assess layer thicknesses. Other uses also established include detection of construction changes, location of voids and wet patches (possible indications of poor support), location of reinforcement bars and location of excess sub-base moisture (indicating poor drainage). 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.

In the 1990's the use of GPR to provide 'network level' surveys was established, and more recent work on the routine use of GPR and FWD surveys has been published, with methodologies for the integration of both GPR and FWD data with other pavement condition data from a pavement management systems recommended (Noureldin *et al* 2003). Despite such studies, and the establishment of protocols for 'routine' GPR investigations, the nature of urban road sites and urban geology mean that performing GPR investigations using 'standard' methodology at urban sites will often not obtain the optimum amount of information.

The dielectric constant of a material will determine the velocity of the radar pulse, so by recording times for reflections to be received, a depth can be estimated. However, as mentioned above, materials generally have a range rather than a specific value. Davis *et al* (1994) showed that asphalt pavement materials tested had a dielectric constant of about 3.5-10 (which corresponded to velocities of 95-160 mm / ns) suggesting that the range of radar signal propagation velocity for in-service pavements could be large. Hence, despite data existing on the dielectric constants of pavement materials and soils, providing layer depths purely using published dielectric constant values is not advisable. It is important when conducting GPR surveys on roads, that actual layer depths are obtained (usually by coring), in order to calibrate the GPR at specific locations on the site, to test the accuracy of the data. This is especially critical in urban locations where the nature of both the road pavement and the underlying ground tends to be more varied than for non-urban sites.

The reported level of accuracy achievable for layer thickness evaluation is varied, and it must be noted that site specific conditions will play a part in this, as well as the GPR data collection parameters used. The 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". In the large majority of cases GPR is a useful non-invasive tool for the engineer and geoscientist, providing valuable information, increasing the understanding of the condition and features of the pavement and ground, and providing cost and time savings. However, it should always be remembered that the physical laws which govern the principles of electromagnetic radar wave propagation dictate there will be circumstances when the usefulness of GPR is limited.

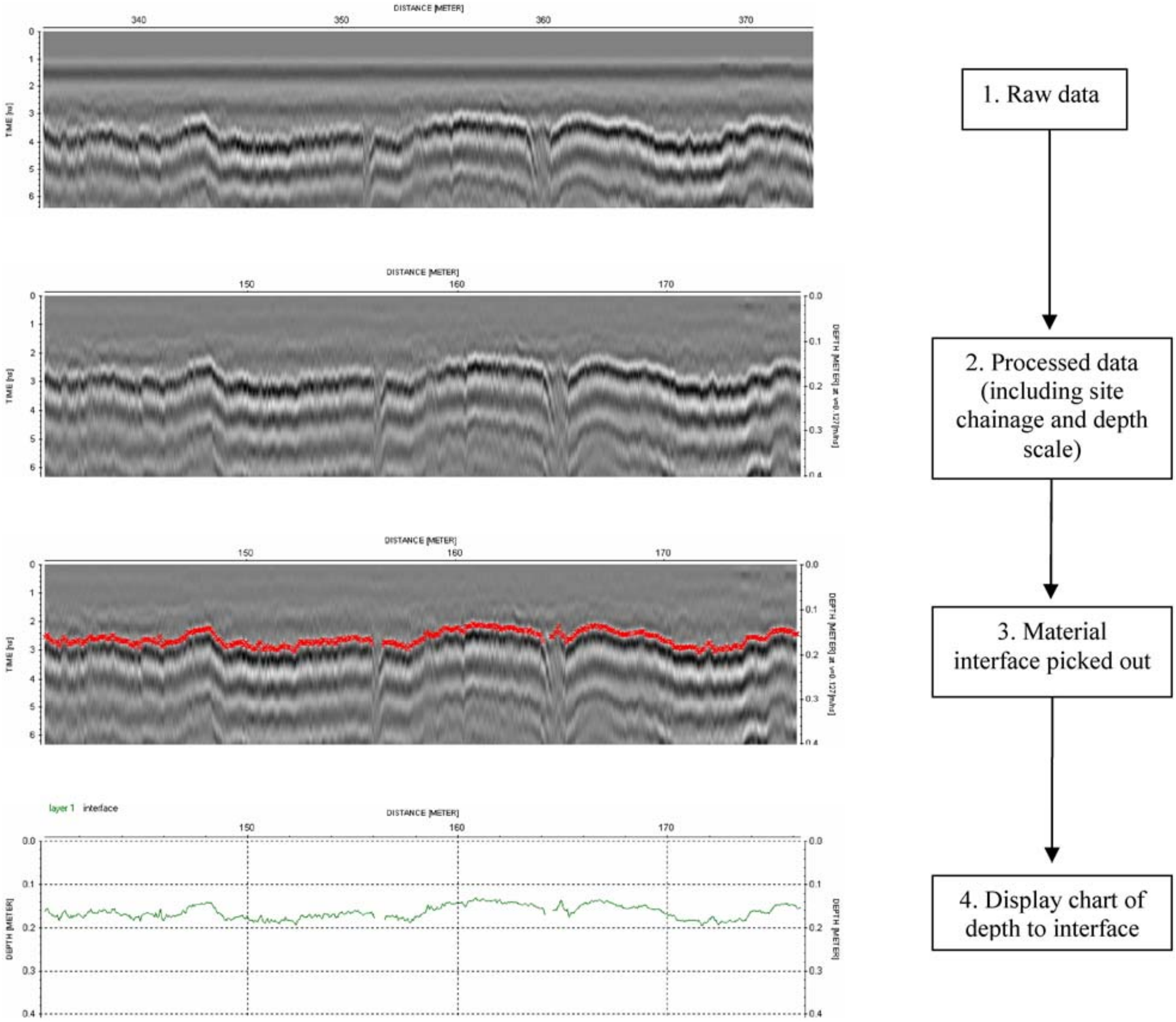

Figure 1. Typical stages in GPR data processing and presentation

URBAN ROADS

A large range of road types exist in urban areas, from low volume local estate roads, through to major access roads and urban motorways. Around the world, whether in developed or developing cities, urban roads are of vital importance to the movement of goods and people, and many countries have seen a large expansion of both their urban and rural road networks in the past few decades. For example, in China the development of the road network in the latter half of the 20th Century was seen as being directly linked to economic growth (Fan & Chang-Kan 2005), and much investment was put into the road network, particularly higher quality urban and inter-urban roads. In 1952 China had a road network of 127,000km, carrying 45.6 million persons. By 1978 these figures were increased to 890,000km of roads, carrying 1,492 million persons and a large surge in investment since the late 1970's saw China in 2002 with 1,765,000km of roads carrying 14,753 million persons.

In many developed countries urban transport involves an integrated network of transportation modes, and urban roads are essential for the efficient movement of goods and people in towns and cities. In Great Britain there has been an almost sevenfold increase in the number of road vehicles in the past 50 years, with commercial vehicle traffic almost trebling (Royal Academy of Engineering 2005). There are several thousand km of urban roads in Great Britain, the large majority of which are unclassified roads (see Table 1), requiring ongoing assessment and maintenance.

Table 1. Lengths of urban road types in Great Britain in 2004*

Road type	Length (km)
Urban trunk	590
Urban Principal	10,548
Urban B road	5538
Urban C road	10,859
Urban unclassified	113,520
Total urban	141,055

*Source: Department for Transport (2005)

Many urban roads in the UK are ‘evolved’ roads, where the road has been subject to periodic overlaying or re-construction as traffic demand and loading has increased over the course of many years or possibly centuries, perhaps developing from a track into a primitive road, into a paved road and finally into a ‘modern’ road structure. Such roads may have variable and non ‘standard’ construction materials particularly in the sub-base and subgrade layers, where new road materials have been laid over the top of the existing structure as the road has evolved. In such situations, the ability to undertake efficient site investigation of the road structure and underlying ground to determine the thickness and nature of the materials is particularly important.

SITE INVESTIGATION OF URBAN ROADS

In the UK the local highways authority (such as the local city council) has the responsibility to maintain urban roads to an adequate level of repair, a situation which is similar to many other countries. Visual surveys are a common technique for routine inspection of road condition and are often used to target further investigation. Areas which require maintenance can be caused by problems in the pavement, sub-base and/or subgrade, and often the first indication that maintenance may be required is noted by the appearance of features such as cracks or rutting of the road surface.

The DMRB contains guidance, which is mandatory for trunk roads, on assessing the condition of roads. Non-UK documents also provide similar guidance, such as the AASHTO Guide (AASHTO 1993) published in the United States. The various techniques described in the DMRB are often also used for the investigation of urban roads. Once areas of a road have been identified as requiring detailed investigation, there are several methods which can be used to determine the properties of the pavement, sub-base and supporting underlying ground, both intrusively and non-intrusively. It is these subsequent detailed investigations that are used to plan maintenance treatments.

The detailed investigations may include intrusive methods such as coring and trial pits (with associated testing within the pit, such as California bearing ratio (CBR) tests, or dynamic cone Penetrometer (DCP) tests. Data from these types of investigations are extremely useful in calibration of non-intrusive investigations, but the more investigations can be achieved non-intrusively the less the damage (and subsequent time and expense to repair) to the pavement structure. A good overview of the in-situ assessment of pavement structural conditions, from a UK perspective, is given by Rockliff (2000).

Two of the main non-intrusive methods used to assess structural condition of roads are deflection testing (using a device such as the falling weight deflectometer, FWD) and GPR. Using deflection as a measurement technique is long established, with some devices dating back to the 1940’s, and various types of deflection test device have evolved over the years. Modern devices such as the FWD can provide information on the deflection of the pavement under load, and this data can be used to calculate the stiffness of the various layers within the pavement structure. The use of radar provides structural information of a different nature, and it has been a much more recent concept over the past 15 to 20 years and it remains a developing technique today.

GPR INVESTIGATION OF EVOLVED URBAN ROAD SITE

As described above, the nature of many urban roads and near surface urban geology presents a more variable and challenging environment than that often encountered in trunk road or motorway investigations. In 2005, a GPR investigation of an urban road site was undertaken, involving GPR data from a number of survey lines. From visual inspection, the surface of the road was showing signs of structural problems, and maintenance was required. Although the general construction of the road was known, little detailed information existed, so before any maintenance could be planned the internal structure of the road had to be determined. The nature of the site meant that a specific site methodology had to be devised in order to obtain the information required to plan the maintenance work. The lessons learnt and methodology devised for the site may prove valuable for the investigation of other evolved and non-‘standard’ urban road sites in the future.

Site details

Information was required on the internal structure of an urban evolved road, in the English West Midlands, running through a local high street with both residential and commercial properties nearby. The construction details of the road were non-standard with regard to DMRB guidelines, and it was thought to be one of a number of similar road structures in the region. A site investigation was conducted to determine whether GPR could provide adequate information to assist in the planning of road maintenance, and also to optimise the GPR methodology used so that it could be used as the basis for designing investigations on other similar roads.

The road had undergone several maintenance and re-surfacing treatments over a number of years, but its foundations had remained largely unaltered. The local near surface geology consisted of silty clay, and in two trial pits excavated at the site a fine ash starter layer of about 50mm thickness was observed above the clay, acting as a bed for the road structure. For most roads in England, depending on the CBR value of the natural ground, a capping or sub-base layer of crushed rock aggregate would be expected above the natural ground. However, the original old road structure placed at this site consisted of stone blocks (cut approximately to the size of cobbles, and locally know as 'pitchings') placed on the ash layer. The current road has been constructed over the top of the pitching layer. Well laid pitchings (often laid by hand, and also knows as 'setts') can form a good load distributing layer, and hence there was no need for a 'traditional' aggregate capping or sub-base layer at the site, because the pitchings could perform the same load distributing function as a sub-base / capping layer would. Above the pitching layer it was originally thought that there was a thin unbound granular sub-base along the entire road, acting as a regulating, or blinding, layer over which the road pavement (i.e. the upper road layer) had been constructed. Intrusive investigations conducted at the site indicated that the sub-base layer was actually highly variable, being 80mm thick in some places, but with no sub-base at all in other places. A bituminous road pavement was in place above the pitchings / sub-base. Figure 2 shows a trial pit excavated at the site.

The bituminous road pavement was generally in a poor condition and contained several areas where previous maintenance had been conducted. Ruts and cracks could clearly be observed on both repaired and un-repaired areas, and maintenance work to plane off of the bituminous layer and replace it with new material was being considered. Information on the depth of the various layers in the road, especially to the bottom of the bituminous layer along the length of the site and on the presence and thickness of sub-base, had to be determined before planing could be planned.

Figure 2. Trial pit showing bituminous road pavement, pitchings and silty clay subgrade

Site investigation

The GPR unit used for the site investigation reported in this paper was a Geophysical Survey Systems Inc. (GSSI) SIR-10H system. The reason for the choice of this particular system was that it can collect data from several GPR antennae at the same time, and during investigations 3 antennae were used, operating at frequencies of 1.5Ghz, 900MHz and 400MHz. This approach meant that rather than a single GPR data set being acquired for each survey line, 3 sets of GPR data were acquired for each line, each at a different frequency. The purpose of this was to maximise the information that could be obtained, bearing in mind the limitations encountered by the resolution / depth of penetration trade-off of GPR systems, described above. Using three separate antennae, rather than one, did not impact the operational ability to perform the investigations, through the use of a purpose-built antennae housing-box towed behind the survey vehicle. This meant that the three antennae were towed as one single unit, enabling on-site towing procedures to be the same as for a single antenna. Each transducer was linked to the SIR-10H data collection unit inside the vehicle, by a 5m cable. Raw data, showing a profile of travel time of reflected radar signals along the length of the survey, was displayed in real-time inside the survey vehicle.

Although the raw data displayed in the survey vehicle gave an indication of the layers and interfaces on site, office based analysis of the data, in conjunction with other site data, allowed more comprehensive and accurate determinations of layer and feature depths and an indication of material type and integrity.

A survey wheel was connected to the antennae, and the rate at which radar pulses (scans) were transmitted (i.e. the number of radar pulses per second transmitted by the antennae) was driven by the movement of the wheel. When connected to a survey wheel, different GPR systems have different maximum scan rates, and this along with the speed at which the antennae move along the ground determines the scan spacing (how many radar data points are collected over a given distance). GPR surveys can be conducted at high speeds, and often network level surveys are collected at vehicle speeds of 40 km/h or above. However, the faster the vehicle speed the lower the number of scans per metre along the survey line. Often for network levels surveys, roads tend to be of a more homogenous nature than urban roads, so radar scans every 0.5m along a survey line is not uncommon.

Slower surveys speeds will, clearly, increase the amount of time required for surveys, but the nature of this site, as with many urban sites, meant that a detailed picture of construction and material features was required. A relatively high-speed survey (and the resulting scan spacing this would produce) may miss details or features of interest. During on-site data collection, the GPR system parameters were set so that a scan was taken approximately every 0.04m along each survey line. This required a slow vehicle speed of approximately 3km / h.

Often, it is common to collect GPR data in one wheel-path per lane for a road investigation. After consideration of the existing information indicating the variable nature of the materials at the site, and the presence of many cracks and ruts on the road surface, it was felt that GPR surveys runs only in one wheel-path may miss important features of the road structure. GPR survey runs were taken in both the near-side and off-side wheel-paths in each lane, and a number of transverse runs were also taken (within the confines of site traffic management). This approach, whilst adding to the time taken to perform the site investigation, meant that a comprehensive picture of the road structure could be collected, and features and properties of the structure could be observed that would have been missed if a 'standard' survey approach had been taken.

GPR data were referenced to local site chainages, which were marked from fixed features which could be easily found if the site was re-visited (such as centre lines of road junctions). It has been known for site chainages to be referenced to parked vehicles, or have descriptions in site notes such as "lamp-post", which prove extremely unhelpful when later trying to establish site locations. The importance of accurate site chainages can often be overlooked during a site investigation, and for sites where changes and features occur at relatively close spacings and short distances, an accurate chainage system becomes even more significant. The most accurate and carefully collected GPR data can become virtually useless if its location on the site is uncertain.

Figure 3. GPR survey vehicle, with antennae housing in towing position

Core locations had been previously taken from the site, and their position on the GPR survey line were recorded by the GPR operator pressing a marker switch which placed a record directly onto the GPR raw data as the transducer box ran over the core locations. Also noted during the GPR investigation were new core locations, which were excavated during the course of the site work. A dialogue between GPR and coring crew was maintained, so that the cores could be taken from locations where the GPR crew judged them to be of more value. This close working relationship between crews performing GPR work and intrusive investigations improved the accuracy of positional correlation between core and GPR data, and allowed feedback from the GPR crew to assist in targeting core locations.

Core information was then later used to calibrate the GPR data. By correlating the material depths provided by cores with travel times for reflected GPR signals at the core locations, a velocity for the radar signal through the road material could be calculated. This calculated velocity could then be used to determine depths within the road structure for the lengths of the GPR survey in between core locations, and is the most accurate technique for determining depths from GPR signal travel time data. In total, 13 cores (old and new) were taken, and approximately 2000m of GPR survey lines were obtained. This number of cores per GPR survey length was relatively high compared to many GPR investigations but the trial nature of the site investigation, and existence of previous core data, facilitated this. The number of cores required for adequate calibration of data for a given GPR survey depends on the homogeneity of the site materials encountered, and will vary from site to site.

The GPR raw data files were processed and analysed using the REFLEXW v3.5 program, for determination of layer depths, and identification of homogenous and anomalous lengths of pavement construction. Several other GPR software packages are also available and are able to perform similar data processing steps. Data was subjected to processing and filtering stages including corrections to allow for the fact that the GPR antennae are not in direct contact with the road surface, background noise removal and conversion of signal travel times to depths within the pavement structure.

Figure 4. Transverse survey across road. The display screen is visible inside the survey vehicle, with SIR-10H unit to its right (connected to the antennae box by three cables).

During the site investigation the methodology employed was reviewed and revised, with the aim of optimising the GPR survey procedure. In order to obtain the most information from GPR investigations as possible, the methodology has to be tailored to the specific site conditions and constraints. This, as with all site investigations, should start with a review of any available existing site information before beginning to plan the on-site investigation, and if necessary the investigation methodology should be revised and tailored as the on-site investigation is conducted.

Information provided to the engineer

The GPR data was collected and analysed as described above, and information on layer depths and material integrity were determined. The information obtained from the GPR data identified three distinct longitudinal pavement sections, rather than a similar construction along the entire road length, consisting of a short section of reinforced concrete slab pavement (about 300mm thick), a long section of poor condition bituminous pavement (about 150mm thick), and a long section of sounder condition slightly thicker bituminous pavement (about 180mm thick). The thickness changes were easily identifiable from the GPR data, and the condition of the pavement material was assessed based on correlations with intrusive investigations and interpolating data from these. Much of the pavement material appeared to be in a poor condition, with areas of sound and partially deteriorated pavement material overlying some areas of badly disintegrated material, sub-base and/or hand pitching. The nature of such materials meant that confidence in identifying discrete layer boundaries in some places was low, because of the mix of materials present (badly disintegrated bituminous material, granular sub-base and some of the smaller particles at the top of the hand pitching layer). However, although the actual layer thicknesses could not be determined with confidence, the presence of these areas (i.e. areas of disintegrated and of poor condition) could be identified. It should be noted that the inability to determine precise layer thicknesses is not just limited to GPR data - there would also be a degree of uncertainty in any reporting of layer thickness from intrusive investigations (cores, or trial pits) in these areas, because of the poor condition of the materials. Several areas of the road appeared to contain wet material, and although these could be identified from the GPR data it meant the radar energy was attenuated deeper down in the road structure, leading to less deeper information being obtained from these sections.

The data from transverse GPR survey lines proved to be very useful. Material thickness in the upper road construction (i.e. the bituminous pavement) tended to be greater in the wheel-paths than in the lane centre line. Without the transverse surveys, this information would not have been discovered by the longitudinal GPR surveys in the lane wheel-paths or by the intrusive investigations alone. Differences of up to 50mm in pavement depths below the road surface were discovered. Bearing in mind the intended maintenance treatment of planing of existing material from the road, this difference between lane centre and wheel-path pavement thickness was an important discovery.

The indication from intrusive investigations that the sub-base layer present in the road was not constant throughout the entire site was confirmed by the GPR data. Some lengths of the road contained sub-base and some did not, and the thickness of the sub-base present was highly variable, from 0 to 80mm thick. The trial pits excavated confirmed that areas of the sub-base, hand pitching and lower pavement layers were very wet. This factor resulted in the GPR survey being unable to identify a distinct boundary lower than the upper level of the hand pitching (although it should be noted that the methodology employed was aimed at providing information to assist with the planning of maintenance treatment involving removal of the bituminous pavement, i.e. identification of the depth of the bottom of the hand pitching was not a primary concern).

The investigation provided information on the presence of discrete sections of similar construction, on the variable depth of pitching (sharp variations within short distances), the absence and where present the thickness of sub-base, and the variable depth and condition of the bituminous pavement. Also, it was discovered that the thickness of the road pavement varied transversely across the lanes. From the information obtained, it can be determined that an attempt to plane material off to the depth of the pitching would be extremely difficult, and planing to the bottom of the bituminous layer (as identified from the GPR data) would be a more appropriate target. Also, because of the transverse variation in pavement depth, planing of material in three distinct runs per lane would be reasonable.

DISCUSSION & RECOMMENDATIONS

Discussion of findings from site investigation

The maintenance plan for the road investigated was to plane off material and re-lay a new pavement. The GPR investigation was conducted to assess how much useful information could be obtained from a GPR survey, to assist with the planned maintenance treatment, and to determine an appropriate methodology for investigating other similar sites. The investigation was successful in identifying a 'safe' planing depth to which material could be removed. However, the use of GPR had limited success in identifying lower material layer thicknesses (although this was less of a priority for this particular investigation). Identification of the bottom of the bituminous pavement was generally successful, but precise identification of lower layers (sub-base and the level of the top of the hand pitching) could only be indicated with less confidence. It is likely that, at other similar sites with deteriorated and variable thin materials in poor condition, the confidence in reporting individual layers would also be variable.

Several factors, which affect the level of information obtained from this investigation, existed during each stage of the process – planning, investigation, processing and reporting. The technical and scientific issues relating to the materials and nature of the site, and to the GPR technology used, were not necessarily the most influential factors. The scientific constraints of the site (limitations of, and laws governing, propagation of electromagnetic radar waves through the specific materials encountered on-site) mean that a change in GPR equipment would be unlikely to alter the significance of the information obtained. The trial nature of the site allowed the on-site data collection methodology to be adapted and optimised to the site specific situation. Also, it is unlikely that changes to the processing procedure of site data (involving several 'standard' steps, plus analysis and interpretation by an engineering geophysicist) would alter the level of information obtained. One of the main issues to obtain best possible results in such a challenging pavement scenario is for the data provided by each member of the investigation team to be integrated effectively. A close working relationship for the investigation team is essential, if the most benefit is to be obtained from the investigation. Discussion and feedback of information from the various teams involved in an investigation, including the coring crew and laboratory staff, GPR survey crew, engineering geophysicist, pavement engineers, project management and client, is essential for the optimum information to be obtained. Ultimately the end user, the highway engineer in this case, has to receive information in a form suitable for assisting planning maintenance.

Recommendations for urban road GPR investigation

Several of the aspects of the methodology employed resulted in an increase in the time required to perform the GPR investigation. This had a resulting impact on disruption to traffic and costs for the investigations. However, it is essential that for an urban site such as the one described here, the appropriate amount of information is obtained to allow engineers to fully assess the condition of the road, and to plan the most appropriate maintenance treatment. It is tempting to try and save time and cost at the site investigation stage of a project, but this can prove disastrous when maintenance work commences only to discover unexpected road and ground conditions. Time spent on the in-situ investigation can lead to overall time savings in the future, by provision of sufficient information to allow the most appropriate treatment works to be conducted. Clearly, judgement is required on the benefits of certain aspects of the site methodology, such as taking multiple survey lines and transverse survey lines, which add time but increase the amount of information provided to the engineer. Time and money saved in the site investigation stage by performing a less than adequate in-situ investigation may result in much greater losses in time and money during the maintenance stage, and also lead to maintenance requirements not being fully assessed, and treatments not addressing the full nature of the problem. The saying "You pay for a site investigation whether you do one or not" holds true.

When conducting GPR investigations of urban sites, as much information as possible should be obtained about the site before any investigation is planned. Information on the nature of the site – age of the road, 'modern' or evolved construction, variable materials or homogenous construction, local near surface geology, etc – will affect the methodology used for the in-situ investigation.

Where urban roads are thought to be of highly variable nature, or there is little information available on the nature of the road structure and underlying ground, it is recommended that the following points are considered:

- Several antennae, providing a range of radar frequencies, should be used to provide the best coverage of depth penetration and resolution. Three antennae of 1.5GHz, 900MHz and 400 MHz would be typical for road structures.
- Despite the disadvantage of taking longer, slow speed surveys (i.e. giving a high number of radar pulses per distance travelled) are recommended for sites with highly variable materials, so trelevant features in the road structure are not missed.
- Along with longitudinal survey profiles in both wheel-paths, transverse surveys across the road are recommended whenever possible.
- Intrusive surveys (usually in the form of cores, but also trial pits) are necessary to calibrate GPR data to a suitable level of accuracy. The number of intrusive investigations will depend on the nature and homogeneity of the site materials.

- Accurate marking of core locations in relation to GPR data points is required. To provide the most accurate correlation of core locations with GPR survey line data, cores should be marked and excavated during the same site work period as the GPR surveys whenever possible. In any case, the core locations should be marked directly on the GPR data pseudo-section.
- Special attention should be paid to a sensible and easy to follow site chainage system, marked from fixed locations on site.
- Discussions should be ongoing between the different members of the investigation team (coring crew, GPR survey team, engineers, project managers, engineering geophysicist, client, etc), to provide a co-ordinated approach to the investigation.
- Team members, and especially the end users of the information, should be made aware of the various uses and limitations of GPR investigations.

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.

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