Sustainable assessment of structures and materials using ground penetrating radar (GPR)

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Abstract

Ground penetrating radar (GPR) is a non-destructive, non-invasive device that can be used to investigate materials in buildings, structures and the ground. Its use relies on recording the reflections of radar waves that are transmitted into materials. This paper provides an overview of GPR, a brief explanation of its principles of operation and application, suggests areas where its use may be appropriate in the context of buildings and structures, and includes some case studies from engineering investigations conducted by the author to highlight examples of the information it can provide. The technical information that GPR can commonly provide includes material depths and thicknesses, locations of excessive moisture or deterioration, and the location of steelwork within construction materials. Whilst reducing uncertainty in data obtained from building and structural investigations, other advantages compared to alternative intrusive investigations include less time and costs for investigations, less disruption to users of the building / structure, and less material required for subsequent repair and maintenance work. This paper also highlights, however, some limitations of the technique which should be considered in order to optimise the success of GPR investigations, such as the necessity for specialist knowledge in operation and data interpretation, and the limited GPR signal penetration within certain materials. Overall, the potential for use of GPR in the determination of material and structural properties in the built environment is highlighted.

Key Words: *Ground penetrating radar, maintenance, material assessment, non-destructive, non-invasive.*

1. INTRODUCTION

The assessment of the conditions and properties of existing buildings, structures and engineering materials is a common requirement in a number of areas of the built environment sector. Obtaining accurate information can sometimes be problematic because of a lack of, or uncertainty with, exisiting records. A potential solution is through the application of ground pentrating radar (GPR) which, in comparison to other investigations methods, can reduce time, costs and damage to materials when assessing existing structures and materials and can also increase certainty (i.e. reduce risk) in knowledge of existing conditions of buildings and structures.

GPR is a material investigation technique which has the potential for sustainable built environment applications such as the assessment of the current condition of structures for maintenance or retrofit, identification of pipework locations, leaks and areas for repair within underground heat distribution networks, and overall can reduce the need for destructive investigations of existing building materials whilst obtaining information concerning their properties and condition. Typically, the type of information that is obtained from GPR includes the thickness / depth of materials, the presence of steel work, location of voids, location of areas of excess moisture and it may also be possible to determine a general appraisal of the overall condition of materials e.g. sound or deteriorated.

This paper provides an overview of GPR, a brief explanation of its principles of operation and application, suggests areas within the built environment where its use may be appropriate in the context of buildings and structures, and includes some case studies from wider engineering investigations conducted by the author to highlight examples of the nature of the information it can provide.

1.1. What is ground penetrating radar (GPR)?

GPR is a non-destructive, non-invasive device that relies on recording the reflections of radar waves that are transmitted into materials. A lack of appreciation and knowledge regarding GPR has in the past led to its capabilities sometimes being overstated, or to it being applied in an inappropriate manner, which can lead to disappointing results. Hence, its use requires specialist knowledge and careful interpretation of data. However, when applied correctly, it is one of the most versatile and useful investigation tools available to the civil engineer. Daniels (2004) provides a comprehensive overview of the technique, including its main applications, limitations and data processing procedures.

Radar waves are a type of electro-magnetic (EM) wave, and there are many different types of EM wave (e.g. gamma-rays, infra-red, ultra-violet, visible light, microwaves, radio waves). GPR EM signals (waves) operate at the radio and microwave frequencies, which is where the acronym “radar” originates (RAdio Detection And Ranging). GPR waves travel through most solid (and liquid) materials, such as concrete, asphalt, brick, rock, soil, fresh water, etc., and when the EM radar signal travels from one material into a second material (e.g. from soil in to rock, or asphalt to concrete, or air to water), some of the radar signal is reflected back from the material boundary and some of the signal continues into the second material (see Figure 1). Note: the reflection of GPR signals at the boundary of two different materials occurs in most situations, but not always. This is discussed further below.

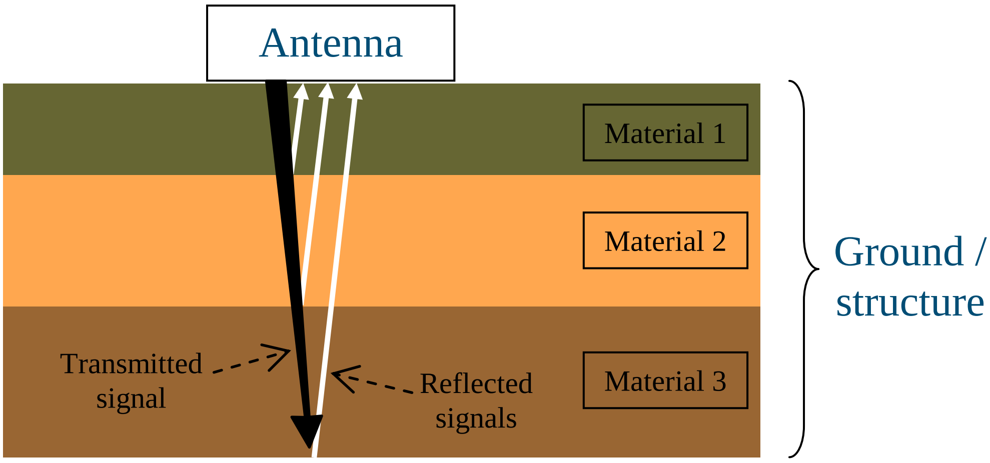


Figure 2. General principle of reflections of GPR signals from a layered structure

1.2. What governs the data obtained from GPR?

The passage of GPR signals through a material are largely governed the materials 'electrical permittivity' (i.e. its ability to store (i.e. 'permit') an electric field (i.e. EM energy) that has been applied to it). This property is often reported as the ratio of the permittivity of the material relative to the permittivity of a vacuum, known as the 'relative electrical permittivity' or the 'dielectric constant' (ε_r). The velocity of a radar wave and the amount of radar energy reflected from a material boundary is governed by the contrast in ε_r values of the two materials.

Another material property which affects GPR signal propagation is electrical conductivity (σ). The higher the electrical conductivity of a material, the more that GPR signals will be attenuated (i.e. signal amplitude will reduce rapidly as it travels through the material). Factors that increase conductivity include a high amount of salts present in water in the material, and the presence of clay minerals. Hence, the presence of water and clay minerals can reduce the effective penetration depth of a GPR investigation.

The frequency and velocity of GPR signals will determine the wavelength (distance between successive EM 'waves'). The higher the frequency of the radar signal, the shorter the wavelength and hence the better the resolution (i.e. precision of data) but the less signal penetration (i.e. shallower depth to which can be 'seen'). However, signal frequency also influences the attenuation of the GPR wave. For example, typical GPR signal penetration depths for a damp sandy soil might be perhaps 0.5m for a signal frequency of 1500MHz, but perhaps 5m at a lower signal frequency of 100MHz. So, there is a compromise: Higher frequency of radar signal provides better data precision but less depth penetration.

1.3. What data can GPR provide?

The type of information that GPR can provide has been outlined above. Common applications where GPR investigations are utilized include in the utility sector for location and condition checks of pipework, road pavement and bridge evaluations for quality assurance or maintenance investigation, archaeological investigations before excavations are conducted, establishing geological settings for geotechnical and mining projects, and for the investigation of ice and snow – for example to monitor glacier thickness. The use of GPR for structural and building investigation is a growing area commercially but one in which there is perhaps not widespread appreciation.

The potential data that GPR can provide is wide ranging, and when considering the entire life cycle and scope of a building or community, there may be several instances where it is essential to establish material or structural properties (e.g. site investigations before construction commences, quality assurance checks during the construction phase, establishment of existing conditions for planning of retrofits, and condition assessments for planning of maintenance works). By providing examples and case studies below (see Section 2) it is hoped that the ability of GPR, as well as its limitations, can be highlighted and that lessons can be drawn on the applicability of GPR in the built environment sector, specifically for its application in relation to sustainable buildings and communities.

Usually, the collection of data involves the GPR antenna being moved along the material surface as distinct 'pulses' are transmitted into the material at set distances apart. A 'detailed' GPR survey might involve pulses transmitted every cm along a survey line. The travel time and amplitude for reflections of the pulses to be recorded back at the antenna are then used to build up a cross section of GPR data on the material being investigated. The travel time of reflected signals can be converted into a depth (if the speed of the GPR signal within the material is known, via calibration or estimation).

2. EXAMPLES OF APPLICATIONS OF GPR

The following section provides some examples taken from the authors experience of structural and material investigation, where several parameters were investigated successfully, but also in which limitations and uncertainties of the technique are highlighted.

2.1. Investigation for maintenance works

Various methods can be used to assess the condition of road pavements, so that maintenance can be prioritized and planned. The ability to acquire accurate information regarding the existing condition of pavements allows the use of finances, materials and resources to be optimized, so that the overall pavement maintenance schedule can be conducted, and the budget targeted, in the most sustainable manner. One key parameter used in road condition assessments is the thickness of the upper structural and lower foundation layers in the pavement (typically asphalt or concrete, and aggregate or soil respectively). For major roads in the UK, a common approach is for a core sample to be extracted from the upper road pavement, along the length of the road of interest, perhaps every few hundred meters (or closer), typically taking 30 minutes to an hour to extract the material and repair each core-hole.

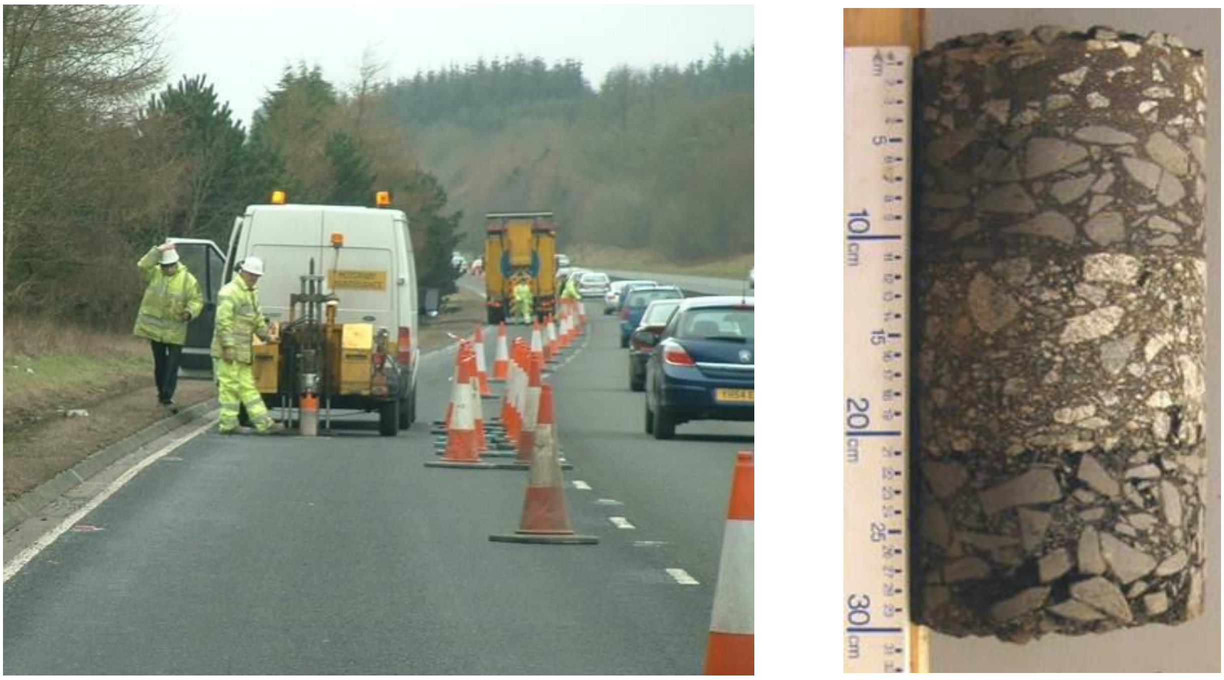


Figure 2. Coring rig extracting asphalt (left), and 300mm thick asphalt core taken from pavement (right)

There are a number of applications of GPR for road pavement assessment (Evans et al, 2008, Saarenketo & Scullion, 2000) and its use along the length of the road pavement prior to coring provides a number of advantages. The speed at which a GPR antenna can be moved along a survey line depends on the density of data collection required (typically for ‘detailed’ GPR surveys, with radar scans every cm along the survey line, speed of movement is limited to a few km per hour - perhaps walking pace - and for less detailed surveys with scans every 0.5m movement can be at normal traffic speed). Traffic speeds surveys can be conducted by attaching the GPR to a vehicle and pulling the antenna along the length of the road of interest without the need to close the lane. Even if the GPR survey is conducted within a lane closure, several km of survey line data can be collected within an hour (the time it may take to extract a single core sample and repair the hole).

Figures 3a & 3b below show GPR data, representing cross-sections, taken from 600m and 400m lengths of trunk road asphalt pavement respectively (scale along the x-axis). The signal travel time, which is a pseudo-depth scale, is plotted down the y-axis. In the plots, a travel time of 10ns is equivalent to a depth in the pavement of approximately 500mm. Figure 3a shows data from a pavement structure that has two distinct layer interfaces at approximately consistent depths along the full length of the cross section. Figure 3b however shows a pavement where multiple layers at varying depths can be identified.

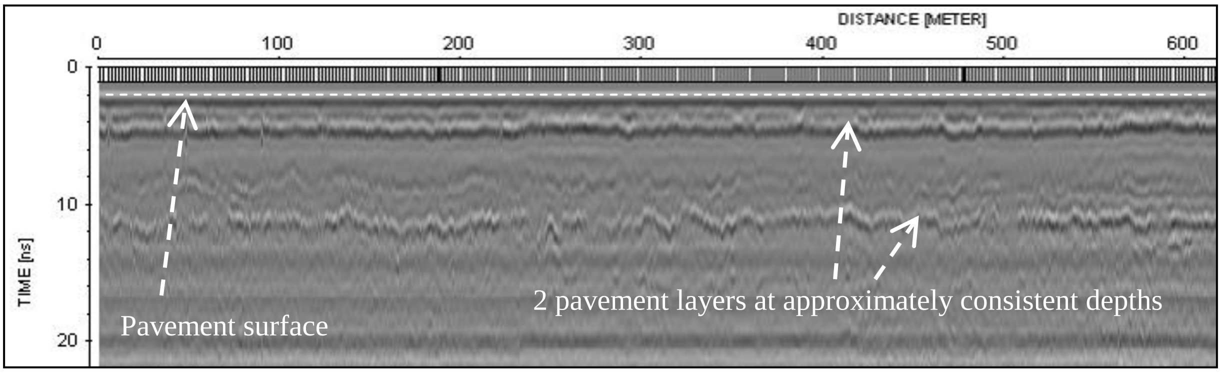


Figure 3a. GPR cross section of homogenous pavement construction

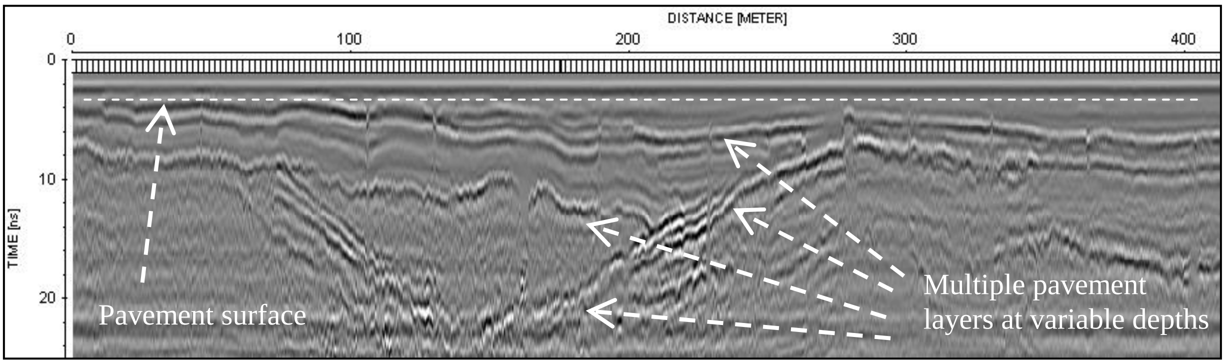


Figure 3b. GPR cross section of variable pavement construction

The data in Figures 3a & 3b can be used to reduce the overall need for coring or to target specific locations for coring that, from the GPR data, appear to be of most interest or uncertainty. A single core taken from the pavement in Figure 3a would likely be representative of the entire pavement structure as there appears to be little variation along its length and so there is no requirement for coring at 100m intervals (which otherwise might be typical). Intrusive coring of the pavement, for both of the examples shown, involving associated costs, time, materials and road closures can be targeted and optimized. In addition to this, depth calibration of the GPR data with any cores that are taken allows accurate pavement layer depths to be determined for the entire pavement length (coring alone only provides depth data at the specific locations where cores are taken), thus reducing uncertainty and providing a much larger data set for the pavement structure.

An important further use of depth data in pavement maintenance assessment is during the determination of the structural capacity of the existing pavement. The thickness of material layers is required to perform calculations of material stiffness, which are then used to assess structural condition and plan maintenance interventions. With core-only data, large assumptions have to be made about the thickness of layers along the pavement length, but GPR data provides a continuous record of layer depths along the entire pavement length, and so the uncertainty in stiffness calculations, and hence in the assessment of structural pavement capacity and subsequent planning of maintenance works, is hugely reduced.

2.2. Moisture within materials

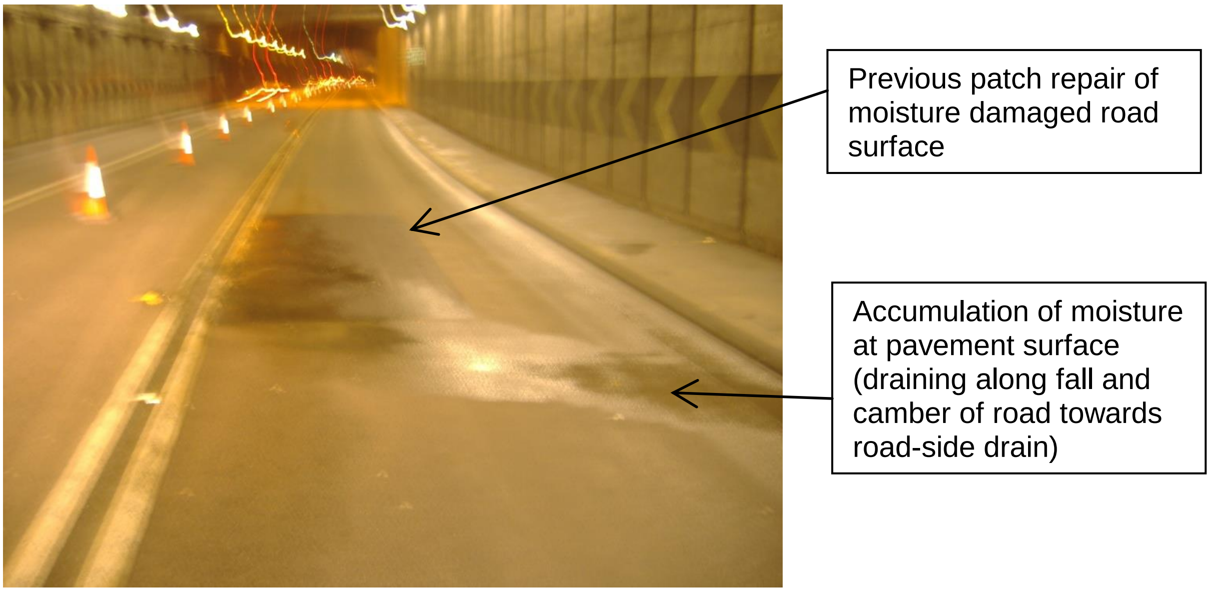
The presence of water within materials can alter their dielectric properties, and hence GPR investigations can provide a way to identify ‘wet’ or ‘dry’ areas of the same material. Excessive moisture within a number of engineering materials can lead to detrimental changes in their properties, e.g. ‘stripping’ of the bitumen binder from the aggregate, freeze-thaw cycles and salt crystallization damage in natural stone and strength reduction of soils. Climate change may also have an on-going effect on such issues, for example a summary of recent work regarding UK historical climatic records has shown that there is strong evidence of a trend towards larger rainfall totals and an increase in the frequency of very wet weather (Osborn & Maraun, 2008, Jenkins et al. 2009). Hence, the ability to detect areas of excessive moisture, or where moisture ingress into buildings and structures is occurring, is likely to be even more important in the future.

The dielectric contrast between materials is enhanced when there are areas of relatively ‘dry’ and ‘wet’ material. Materials containing elevated amounts of moisture, relative to adjacent material, produce high amplitude GPR signal reflections and recording this effect during a GPR survey can be indicative of areas where moisture has accumulated.

Sections 2.2.1 & 2.2.2 below briefly illustrate examples of GPR investigations into moisture presence and ingress into structures.

2.2.1. Eastway tunnel, London, UK

The Eastway road tunnel in London suffered from a small area, towards one of the tunnel portals, where water had entered the pavement material and caused damage to the road structure. Visual inspection provided information on surface water accumulation, but inconclusive evidence of the path of water ingress, or of water accumulation within the pavement, and so a GPR investigation was conducted.



Previous patch repair of moisture damaged road surface

Accumulation of moisture at pavement surface (draining along fall and camber of road towards road-side drain)

Figure 4. Water accumulation at pavement surface

The road construction was a ‘composite’ pavement, which is characterized by a layer of asphalt on top of a layer of concrete (on top of the road foundation). GPR investigations were conducted on survey lines extending along and beyond the area of the road surface where moisture was present. These investigations indicated a number of discrete locations below the pavement surface where GPR signal reflections from the interface between the asphalt and concrete were of greater amplitude than in other areas (indicating a greater dielectric contrast between materials, thus indicating areas of elevated moisture content). In this way it was possible to identify the areas below the surface where moisture was entering and accumulating within the road structure.

An example of a cross section of GPR data taken from a 10m length of pavement is shown in Figure 5. The pavement structure consisted of approximately 200mm of asphalt overlying a reinforced concrete slab. The specific locations where the amplitude of the signal reflection from the asphalt-concrete boundary was increased could be identified as ‘brighter’ areas on the GPR data (see Figure 5). By conducting a number of survey runs in a grid pattern over the pavement surface, the area affected by moisture ingress could be identified.

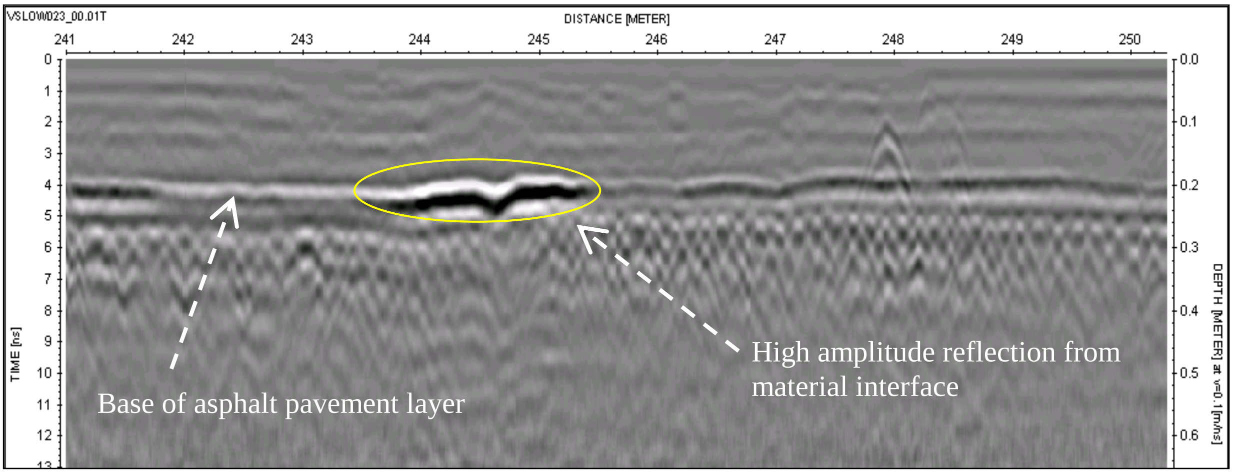


Figure 5. GPR cross section showing presence of moisture at pavement layer interface

Following the GPR investigation maintenance works could be designed and targeted, which resulted in a saving of time, cost and materials for the repair of moisture damage compared to alternative investigation methods (i.e. exploratory excavation or coring).

2.2.2. A2 motorway, Poland

Following the construction of the A2 motorway between Poznan and Warsaw, in Poland, some sections of the newly constructed pavement showed signs of deterioration much sooner than would normally be expected. Initial visual and intrusive coring investigations indicted that moisture was entering the pavement structure at some locations along the motorway, within the upper asphalt layer, and remaining present within the asphalt for a period of time, hence producing the increased rate of deterioration of the structural integrity of the pavement.

A large scale GPR investigation was conducted along several km of the motorway with the aims of identifying any possible defective areas, establishing the integrity of the pavement and finding the cause of the moisture being retained within the pavement layers. As with the investigation on the Eastway Tunnel (see Section 2.2.1), discrete locations within the pavement could be identified where high amplitude GPR reflections were occurring. However, rather than occurring at material boundaries (as with the asphalt-concrete boundary in the Eastway Tunnel), the high amplitude reflections occurred within the asphalt layer itself.

During pavement construction, the asphalt pavement is constructed by compacting thin individual layers of asphalt to create the final thicker upper asphalt layer. High amplitude reflections occurred from a generally consistent depth within the pavement (60 to 180mm depth), and so it appeared that one of the individual asphalt layers contained excessive moisture whilst those above and below it did not. The GPR signal reflections were created by the contrast between 'wet' asphalt and 'dry' asphalt layers. Such a scenario may result from inappropriate material design (too many void spaces in the material), poor compaction of a layer during construction, or possibly inadequate drainage for the pavement.

A number of parallel GPR survey runs were conducted along the length of the motorway, which allowed comprehensive identification of locations of high amplitude reflection (i.e. moisture). Rather than presenting GPR data in a number of cross sections, the GPR data was presented by analyzing the data from a plan-view perspective. On the plan view, the locations along each survey run where moisture was indicted were marked and a 'map' of moisture locations (detected at 60-180mm depth) was created. Figure 6 shows one of the 'moisture maps' created, along a 100m length (and 6m width) of motorway pavement.

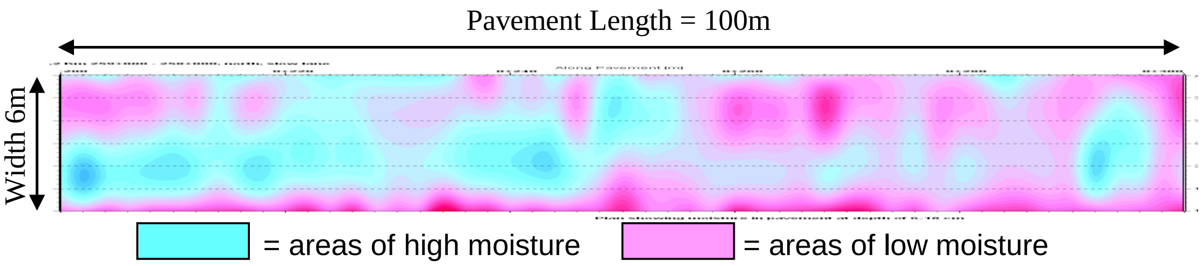


Figure 6. GPR cross section showing presence of moisture at pavement layer interface

The 'dry' layers appearing above the 'wet' layer indicated moisture ingress was not from the pavement surface, and the GPR investigation allowed areas of moisture ingress and moisture presence to be identified within the asphalt layer. Poor drainage at the sides of motorway was identified as the source of ingress, and targeted cores in the pavement confirmed the findings of the GPR investigation. The use of GPR reduced uncertainty about the source and location of moisture removed the need for costly and time consuming intrusive exploratory excavation work, also reducing the requirement for materials used for repair work

2.3. Investigation for redevelopment of existing structure

Staythorpe power station in Nottinghamshire, UK, is a 1650MW gas fired power station that began full commercial operation in 2010. Previously the site had housed two coal fired power stations and so the re-development of the site required extensive demolition and construction work. Part of the work included an investigation of the structural capacity of the existing water pumping house, to assess whether it could be re-developed as part of the new gas power station or whether it was to be demolished.

Records of the bearing capacity and structural form of the floor slabs were incomplete and so a GPR investigation was conducted as part of the floor slab assessment. An example of data from the GPR investigation is shown in Figure 7, which shows a 7m length of one of the GPR survey lines taken from the pump house floor. The cross section shown identified that there were two types of floor slab (unreinforced and reinforced), which was previously unknown from visual inspection and existing records, and allowed a determination of the thickness of the unreinforced slab, and of the location of steel reinforcement within the reinforced slab.

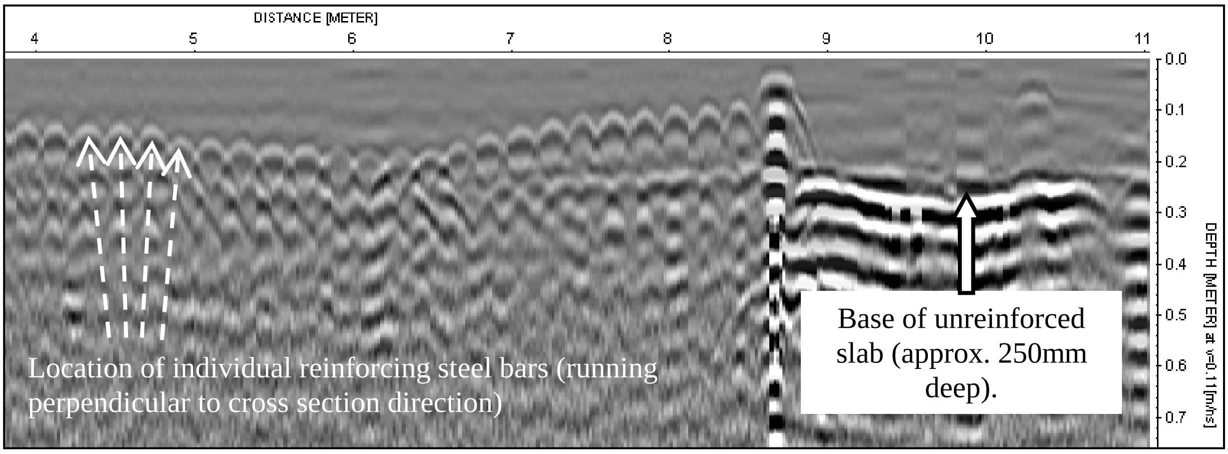


Figure 7. GPR cross section showing features within a concrete slab floor

Figure 7 also highlights one of the limitations of GPR investigation. For the reinforced slab, although the size of the reinforcing bars can be estimated, and locations and depths accurately determined (the variation in depth can be clearly seen), the metal reinforcing bars themselves prevent much of the GPR signal from penetrating further in to the slab, and so information from below the level of dense reinforcement is inconclusive.

3. DISCUSSION

The examples described in Section 2 illustrate some of the applications of GPR for structural and material assessment. The uses described include:

- Depth / thickness determination of material layers.
- Presence of moisture within construction material.
- Location of steel work within construction material.
- Identification of discrete locations within materials which contain differing properties.

These applications have been conducted to establish the existing conditions within structures and materials with several aims in mind, including:

- Identification of material defects and deterioration.
- Provision of input data for structural assessments.
- Planning of detailed intrusive investigations.
- Planning of maintenance treatment.
- Planning of re-use of existing structures.

Other uses not covered in detail in Section 2, but which also may have relevance for use within the context of buildings and structures, include the locations of pipes and utilities and potential identification of defects or leaks within pipe networks, and for general site and ground investigations before construction work commences.

The accuracy to which GPR can locate features within structures or the ground depends on the GPR system settings and GPR antenna frequency (which are decided by the GPR operator), but also on the nature of the materials being investigated (which are beyond the control of the operator). Generally, for shallow investigations (perhaps up to a meter deep) depths and thicknesses can be located to within 1-2cm accuracy, but it should be noted, as stated earlier, that certain materials may inhibit the passage of GPR signals (e.g. high clay content soils, high moisture content materials, dense reinforcement / metalwork).

4. CONCLUSIONS AND RECOMMENDATIONS

GPR has huge potential for use in the determination of material and structural properties in the built environment. Advantages provided by the use of GPR (compared to alternative intrusive investigations) include:

- Less damage (i.e. less requirement for intrusive material investigations).
- Less use of materials (e.g. less requirement to repair damage from intrusive investigation, improved targeting of locations for repair of existing material).
- Less time taken for investigation.
- Less disruption to public or users of the structure under investigation.
- Improved certainty in data obtained (compared to alternative inspection methods).

GPR provides a viable option for the sustainable assessment of buildings and structures, but several important limitations should also be noted, including:

- It is a specialist technique which requires specialist knowledge of GPR systems and data processing.
- The accuracy of GPR depth data is improved if calibration (with known thickness data) is possible.
- Some material types & conditions inhibit the passage of GPR signals and are therefore less likely to provide successful GPR investigation results.

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