

NDT of historic buildings using GPR

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The value of the Ground Penetrating Radar (GPR) technique in the investigation of historic buildings is gaining increasing recognition. Initially developed for geological and ground engineering investigations, GPR surveys have proven to be very useful in the rapid – and non-destructive – location of metal structures such as cramps, dowels, beams and bolts within the structure of historic buildings. Particular success is also recorded in the measurement of material thickness in facing stones. This article seeks to offer recommendations for the design of surveys, the post-acquisition treatment of the data, and the appropriateness of specific target types for GPR surveying.

Introduction

There is an increasing need to inspect and investigate historic buildings without damaging the fabric, or disturbing the users. In response, recent advancements have been made in NDT technologies that can rapidly establish the nature and extent of problems to inform effective remedial and maintenance strategies. GPR is one such technique. It has been used successfully in a number of investigations, offering the potential for much wider application. However, to gain wider acceptance, the benefits and capabilities of the technique need to be carefully defined and communicated to potential users. The successful deployment of GPR to a number of historic building projects provides a basis for a critical evaluation of the technique.

The GPR technique

GPR operates through the use of electromagnetic (EM) waves of frequencies between 50 MHz and 1.5 GHz which are transmitted into the subsurface. A transmitting antenna is used to generate a short (<20 ns) pulse of EM waves of specific frequency (determined by the design of the antenna deployed). This EM pulse propagates through the subsurface and is reflected back to the instrument at boundaries between materials with contrasting dielectric properties. The amount of energy reflected is dependent on the contrast, with greater contrasts generating stronger reflections.

A dielectric material is a substance that is a poor conductor of electricity, but an efficient supporter of electrostatic fields. A useful, if somewhat oversimplified analogy, can be drawn with the propagation of elastic waves in a solid. An elastic wave is represented by the propagation of relative displacement of material, which is resisted by the elastic restoring properties of the material. An EM wave propagating through a dielectric solid is represented by a charge separation, which is resisted by the electric forces between charge pairs in the material.

In general, construction materials such as stone and concrete are good dielectric solids. Metals are very conductive, and as such are very poor dielectric solids. Therefore, the boundary between

typical construction materials and internal metalwork constitutes a very strong contrast in dielectric properties, and a correspondingly high-amplitude reflection is generated.

Higher frequency antennae provide high-resolution data over shallow depths (<0.5 m), and are mostly deployed for near-surface structural investigations. The lower frequency antennae can probe to greater depths (up to 30 m, dependent on subsurface conditions) but exhibit a reduced degree of resolution. Typically, for structural investigations, such as the investigation of historic buildings, high-frequency, high-resolution antennae are deployed in order to image accurately features of interest close to the surface of the structure.

In order to maximise the fraction of the energy that is directed into the structure, it is important to eliminate, where possible, any air-gaps between the base of the antenna and the survey surface. If an air-gap is present, then the most significant material contrast the EM pulse will encounter is that between the air and the survey surface. A large reflection from this interface will significantly reduce the amount of energy that propagates into the subsurface, and may therefore prevent the identification of significant reflections in the data from deeper structures. In some cases it is not possible to avoid air-gaps due to, for example, difficult access conditions or the presence of ornate or fluted stonework. In these situations the data collection strategy and equipment parameters should be adjusted by the operator in order to best compensate. It is therefore important that a professional experienced in the theory and application of GPR technology be consulted at an early stage in the project in order that the utility and likely success of a GPR survey can be evaluated and, furthermore, that this expertise is available at the data collection and data processing stages.

Data processing

The obvious purpose of processing the collected data is to remove spurious or unwanted signals, and to enhance those signals in the data that relate to the target(s) of the survey. Before any processing can be undertaken, therefore, a judgement must be made as to the likely nature and position of reflections pertaining to the survey targets. In other words, you need to know what you are looking for in order to find it. The corollary is that care must be taken to avoid enhancing spurious signals that provide an expected but incorrect interpretation.

There are a number of processing steps that may be undertaken at the data interpretation stage. Each step has benefits as well as disadvantages. Some commonly used processing steps are listed as follows, with comments regarding their use.

Gain control

Absorption, partial reflection and geometric spreading all act to reduce the amplitude of the EM pulse as it propagates through the material. Therefore, the deeper the interface in the structure, the lower the amplitude of the reflected EM signal. In order to compensate for these effects, later reflections are amplified such that the signal amplitude with depth is constant. This adjustment is usually made by a user-defined function, which carries with it certain assumptions. The amplitude function of an EM pulse through a homogeneous material is relatively simple, and can in

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some circumstances provide an adequate template for the gain control. If the subsurface is heterogeneous, containing significant contrasts in material properties, a more sophisticated function may need to be applied. Failure to do so may over emphasise reflections from a particular distance range and eliminate or mask important reflections elsewhere in the data. Gain control is often the first processing step applied to the collected data and is the most important to get right.

Filtering

A typical EM pulse does not contain one frequency of radiation, but a range of frequencies centred about a peak frequency. Filtering the data can help to isolate the legitimate returns from the EM pulse and eliminate lower or higher frequencies that may be present in

the data either from random noise or some external source. Most filtering operations are safe and easy to use, and it is difficult to accidentally remove useful information from the data.

Background removal

This is a spatial filter that acts to remove signals from the data that are horizontally persistent. If targets are expected to produce discrete reflections in the data it is sometimes useful to remove the surface reflection, and perhaps other deeper reflections associated with material contrasts (for example the back of facing stones) that may be consistent across the surveyed area but of no direct interest to the interpretation. Dependent upon the algorithm used it is possible to unintentionally remove discrete reflections from the data if they lie very close to horizontally continuous reflections. The data should be carefully reviewed before this processing step is performed to avoid the accidental removal of discrete features of interest, and background removal should only be done if deemed absolutely necessary. In most cases it is possible to discern the presence of discrete reflections, for example by edge diffractions, even if they are partially obscured, and therefore background removal is not required.

Migration

Whilst the reflections from a pulse are assumed in the data to have originated from directly beneath the antenna, it is possible that some of the reflection events originate from objects located off to the side. This phenomenon creates geometric distortions in the data that in some circumstances it is useful to remove. However, small objects with high dielectric contrasts such as metal dowels are in some instances only visible by the hyperbolic reflection pattern that they generate. If this is removed by migration it may no longer be possible to identify the object from the data. Another consideration is that, for migration to be effective, an accurate model of the velocity of the EM pulse through the different materials in the subsurface is needed. In some instances this can be calculated from the reflection data (for example by analysis of the hyperbolic

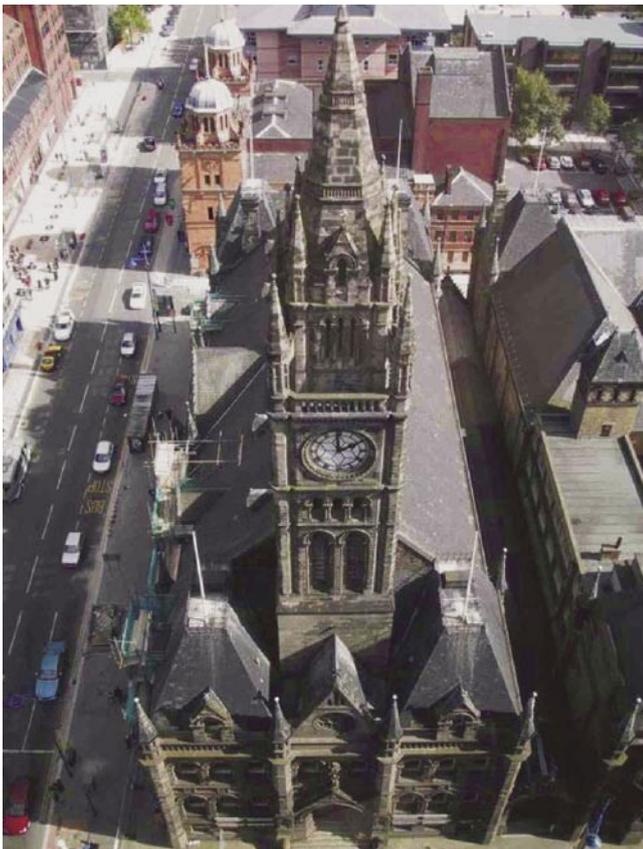


Figure 1(a)

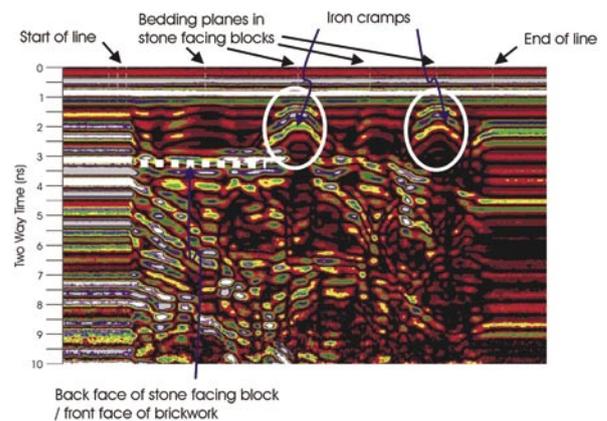


Figure 1(c)

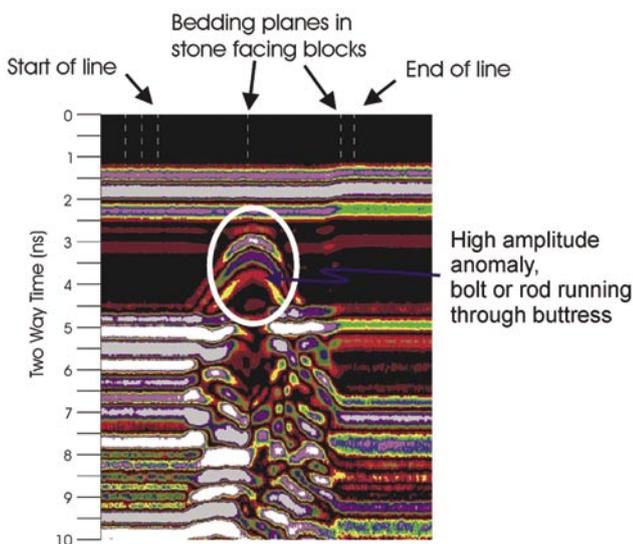


Figure 1(b)

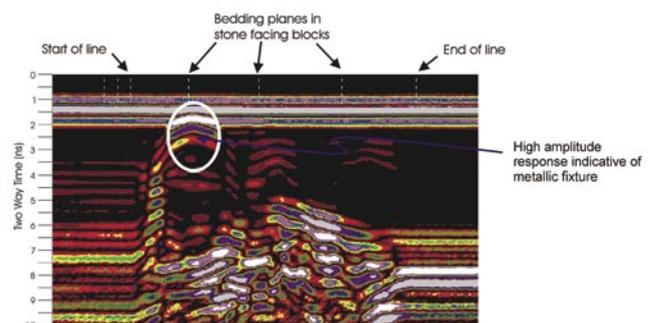


Figure 1(d). GPR survey of Middlesbrough Town Hall Clock Tower. Example radargrams

reflections from small objects); in other cases it must be estimated, or material removed for lab analysis.

Deconvolution

For sharp precise reflections, the pulse shape of the EM signal should be as close to a spike as possible. In practice, of course, physical limitations dictate that it is not. Deconvolution acts to collapse the reflected pulse signal to a spike, and therefore allow smaller objects or thinner layers to be resolved in the data. This is a complex mathematical operation, and as such can produce some unstable results in some data sets. In most cases the deconvolution operation acts to greatly amplify any noise in the data. The operation may also remove legitimate reflections, or introduce false reflections. The technique is most useful in resolving layer boundaries that are very closely spaced, or in removing reverberating signals through the data (for example those caused by very near surface metal).

Illustrative case study – Middlesbrough Town Hall Clock Tower, UK

The GPR survey was undertaken by STATS Ltd in partnership with Middlesbrough Council. The principal purpose of the survey was to identify the presence, depth and dimensions of metal cramps within the spire and the clock tower. Visual inspection had revealed that bed joints between some of the large stone facing blocks in the spire had begun to open up. It was suspected that this was due to weathering processes causing corrosion and expansion of the metal fixings.

The survey was undertaken with a SIR-2000 Radar System, incorporating a 1.5 GHz antenna, and was completed within two days. As expected, the large contrast in dielectric properties between iron cramps and the surrounding stonework produced strong reflections in the radar data, however a number of other features of interest to the engineers designing and undertaking the remediation work were also clearly discernable in the collected data (Figure 1).

In particular, bedding structures within the stone facing blocks produced clear reflections. It is unlikely that each peak in the data represents an individual bedding plane, however the data suggests planar variation in the properties of the material running parallel with the surface. Also clearly visible in the data was a reflection from the back face of the facing blocks. Correlation of this reflector across adjacent lines provided valuable information on the thickness of individual facing blocks, and also the distribution of facing blocks of differing sizes.

Other examples

Figure 2 shows some example data taken from other surveys of historic buildings. The details of these surveys are not available for publication, however the Figures are provided to further illustrate the conclusions. As a result of these and other surveys it has become clear that the integration of GPR data with other surveying methodologies can prove invaluable for the confident interpretation of the data. In particular, the integration of GPR surveys with traditional intrusive surveying has been very successful. Not only has this approach provided invaluable ‘ground-truthing’ information to aid the processing and interpretation of the radar data, but the radar survey can also feed directly into the design on the intrusive survey. The information gained by both techniques is maximised, and the scale and cost of the intrusive phase of the survey can be reduced.

Conclusions

Metallic targets are readily identifiable in GPR data, and can be accurately located without corroboration from intrusive investigations. An appropriate expert with prior knowledge of likely construction techniques may establish the precise nature of

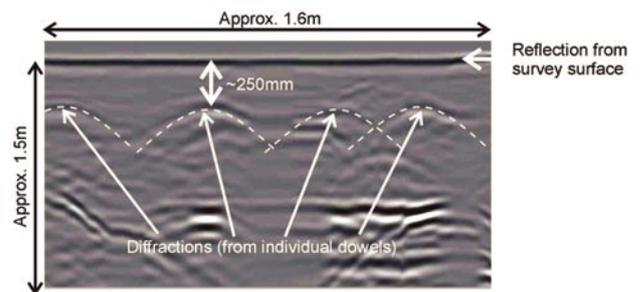


Figure 2(a)

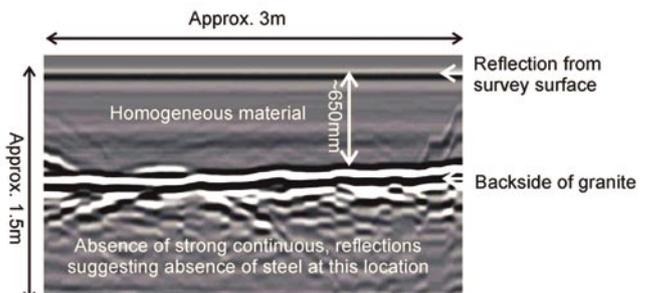
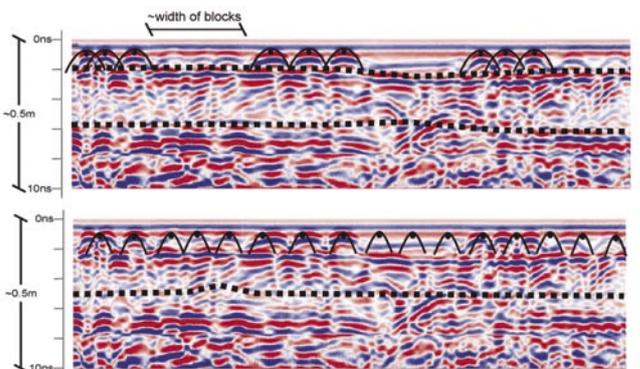


Figure 2(b)



Radargrams collected over two supporting columns. Differences in block geometry and reinforcement prove that these columns were constructed in different ways, and confirmed previous suspicions that they had been constructed at different times

Figure 2(c). Further examples of GPR data from historic buildings. Example radargrams

metallic structures. However, where the nature of a metallic target is ambiguous, intrusive investigation may be unavoidable. In these cases the intrusive phase of the works can be minimised by precise targeting of interpreted features in the GPR data.

Where there is a clear contrast between material types, for example granite facing blocks over bricks, the thickness of outer material can be established with reasonable accuracy using radar data and knowledge of material type alone. Other target types such as delamination or voiding may represent more subtle reflections in the radar data, and as such it would be unwise to rely on radar data alone. In these cases, areas of possible/suspected voiding identified by radar should be calibrated/corroborated by other methods.

In general, great care must be taken in the processing of collected data, and in many cases ‘less is more’. Over-processing of the data may introduce artefacts that could be misinterpreted, and may also accidentally remove genuine reflections. Where more extensive processing is required to isolate and identify particular structures, experience in the handling and manipulation of radar data is paramount.

The success of this type of investigative survey requires the combined expertise of a GPR professional and an engineer with knowledge of the building type. This expertise should be brought to bear at the planning, data collection and interpretation stages of a project.