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Fundamentals of ground penetrating radar in environmental and engineering applications

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Abstract
Ground Penetrating Radar (GPR) is a high frequency electromagnetic sounding technique that has been developed to investigate the shallow subsurface using the contrast of dielectric properties. The method operates on the simple principle that electromagnetic waves, emitted from a transmitter antenna, are reflected from buried objects and detected at another antenna, acting as receiver. GPR data is presented in the form of time-distance plots that are analogous to conventional reflection seismic records, and in fact the method has many similarities to seismic reflection method with a pulse of electromagnetic energy substituting for the elastic (seismic) energy. Nevertheless, the principles and theory of the method are based on the wave equation derived from Maxwell's equations for electromagnetic wave propagation. This paper has been written for tutorial purposes, and it is hoped that it will provide the reader with a good outline of GPR presenting an overview of its theoretical basis, guidelines for interpretation and some practical field examples.

Key words *ground penetrating radar – GPR – cavity detection – horizontal drilling*

1. Introduction

Since the mid-1980's, ground penetrating radar has become very popular, particularly for engineering, environmental and archaeological applications. Because of this interest, two of the most recent published handbooks on applied geophysics, such as Reynolds (1997) and Sharma (1997), have devoted a chapter to this method. The interest in GPR technique is also supported by the organisation of an International Conference every two years: Tifton-1986; Gainesville-1988; Lakewood-1990; Rovainiemi-1992; Kitchener-1994; Sendai-1996; Lawrence-1998 and Sydney-2000. Furthermore, three monographic issues have been edited by Owen (1995), Sato and Versteeg (1998) and Allen and Plumb (2000) in the *Journal of Applied Geophysics* and many papers have been published in other specialised journals (*Geophysics, Geophysical Prospecting, European Journal of the Environmental and Engineering Geophysical Society*, etc.).

There is a wide acceptance of the radar method in certain areas of civil engineering, such as road pavement evaluation, void detection and behind tunnel linings. There has also been an expanding role for the method in geological and environmental applications, particularly in the rapid assessment of superficial deposits, location of shallow sinkholes in karstic areas, etc. Furthermore, in archaeological studies, GPR has been used on many sites to identify potential excavation areas.

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As with seismic waves there is a trade-off between depth of penetration and resolution. For geological applications, where depth penetration tends to be more important than very thin resolution, antennae with frequencies ranging from 250 to 25 MHz are used. For engineering or Non-Destructive Testing (NDT) applications, antennae with frequencies of 250 MHz and greater are used, typically as high as 900 MHz or 2 GHz.

2. Principles of operation

Any GPR system includes a signal generator, transmitting and receiver antenna, and a control unit having digital recording facilities (fig. 1). The impulse radar transmits electromagnetic pulses of short duration into the ground from the transmitter antenna. Pulses radiated from the antenna are reflected from various interfaces within the subsurface and are picked-up by the receiver antenna (Daniels, 1989). Radar reflections will be returned from any natural or man-made object that has a contrast in its dielectric properties.

The dielectric permittivity relates polarisation or electric displacement $\boldsymbol{D}$ to the applied field $\boldsymbol{E}$

$$\boldsymbol{D} = \varepsilon \boldsymbol{E}.$$

Permittivity is often expressed in terms of the permittivity of free space ε_0 in terms of relative dielectric permittivity

$$\varepsilon_r = \varepsilon / \varepsilon_0$$

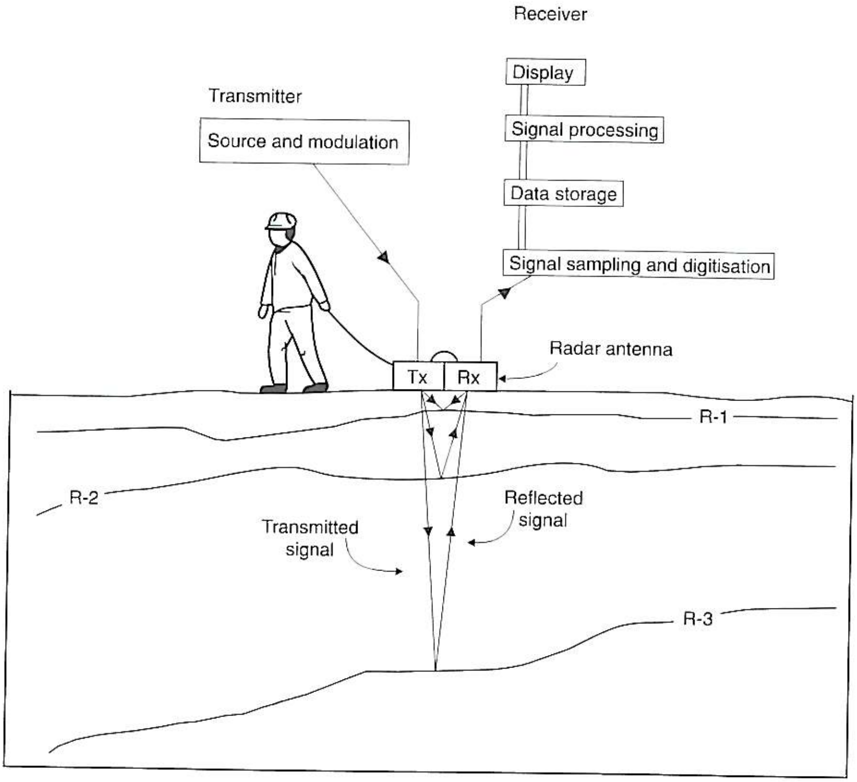

Fig. 1. Sketch of the basic components of a GPR system and principle of operation. Modified from Reynolds (1997).

ε_0 and ε have units of coulombs/volts × m or farads/m, whereas ε_r is dimensionless.

ε_r varies from its space value of 1 to a maximum of 80 for water. ε_r is strongly frequency dependent in parts of the electromagnetic spectrum, and should more properly be portrayed as complex. For most purposes these aspects can be ignored; we will encounter ε_r only at ground penetrating radar frequencies, in the range 10 to 1000 MHz.

With a dielectric permittivity of 80, water dominates the permittivity of rock water mixtures

$$\varepsilon_t = (1-\phi^2)\varepsilon_s + \phi^2\varepsilon_w.$$

The speed of radiowaves in any medium is dependent upon the speed of light in free space ($c = 0.3$ m/ns), the relative dielectric constant (ε_r) and the relative magnetic permeability ($\mu_r = 1$ for non magnetic materials). The speed of radiowaves in a material (v_m) is given by

$$v_m = \frac{c}{\frac{\varepsilon_r \mu_r}{2}\left[\sqrt{(1+P^2)}+1\right]}$$

where:

c is the speed of light in free space;
ε_r is the relative dielectric permittivity;
μ_r is the relative magnetic permeability;
P is the loss factor, such that $P = \sigma/\omega\varepsilon$;
σ is the conductivity;
$\omega = 2\pi f$, where f is the frequency;
ε is the permittivity = $\varepsilon_r \varepsilon_0$, and
ε_0 is the permittivity of free space ($8.854 \times \times 10^{-12}$ F/m).

In low-loss materials, $P \approx 0$ the speed of radiowaves

$$v_m = \frac{c}{\sqrt{\varepsilon_r}} = \frac{0.3}{\sqrt{\varepsilon_r}}.$$

The success of ground penetrating radar method relies on the variability of the ground to allow the transmission of radiowaves. Depth of penetration is a function of the radar signal attenuation within the subsurface media. This attenuation consist of electrical loses, scattering loses and spreading loses. The primarily factors controlling electrical attenuation of the electrical conductivity of the subsurface and the radar frequency. An increase in either subsurface conductivity or the radar frequency will result in greater attenuation of the radar signal.

Some materials, such as polar ice, are virtually transparent to radiowaves. Other materials, such as water-saturated clay and saltwater, either absorb or reflect the radiowaves to such an extent that they are virtually opaque to radiowaves. It is the contrast in relative dielectric permittivity between adjacent layers that gives rise to reflection of incident electromagnetic radiation. The greater the contrast, the greater will be the amount of radiowave energy reflected. The proportion of energy reflected, given by the reflection coefficient (R), is determined by the contrast in radiowave velocities, and more fundamentally, by the contrast in the relative dielectric permittivity of adjacent media.

The amplitude reflection coefficient is

$$R = \frac{(v_1 - v_2)}{(v_1 + v_2)}$$

where v_1 and v_2 are the radiowave velocities in layers 1 and 2 respectively, and $v_1 < v_2$.

Also

$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}}$$

where ε_1 and ε_2 are the respective relative dielectric permittivities (ε_r) of the layers 1 and 2, applicable for incidence at right-angles to a plane reflector assuming no other signal loses and refer to the amplitude of a signal. In all cases the magnitude of R lies in the range ± 1. The proportion of energy transmitted is equal to 1-R.

GPR antennas are often identified by its approximate centre-band frequency (*e.g.*, 50 MHz, 200 MHz, etc.). In general, a high frequency antenna has a higher resolution and lower depth penetration (higher attenuation) than low frequency antenna. The transmitter and receiver may be separate, or the same antenna may be utilised to transmit and receive the signal. A system with a separate transmitter and receiver is called *bistatic*, while a system utilising the same antenna for the transmitter and receiver is called a *monostatic* system. High frequency antennas are *shielded*, so that only the downward-directed signal is transmitted and received. Low frequency antennas (< 200 MHz) are rarely shielded, since it is usually very difficult to absorb the wavelength signals.

Radar systems can be arranged in three basic modes, which are designated as reflection, common-mid-point and transillumination (fig. 2a-c). Reflection is the most common mode of operation. Wide-Angle Reflection and Refraction (WARR) and transillumination measurements are mainly used in velocity analysis, whereas transillumination is used in cross-hole tomographic configurations with the transmitter antenna in one borehole and the receiver down another.

3. GPR survey design

The procedure for recording radar sections in the field is similar to other geophysical profiling and sounding techniques. Effective ground penetrating radar surveys involve considerable planning if the surveys are to meet pre-defined objectives. The most important step in a ground penetrating radar survey is to clearly define the problem. This step is not unique to radar but common to all geophysical techniques although often overlooked in the urge «to rush off and collect data». There are six main parameters to define for common-offset, single-fold GPR reflection surveys (Annan and Cosway, 1992):

Operating frequency – Election of the handling frequency for a radar survey is not simple. There is a compromise between spatial resolution, depth of penetration and system portability. As a rule, it is better to trade off resolution for penetration. Obviously, there is no use in having great resolution if the target cannot be reached. A simple guide is to use the following formula:

$$\log_e f = -0.95 \log_e z + 6.15$$

where f is the operating frequency and z is the required depth of investigation.

Estimating the time window – The way to estimate the time window (tw) required is to use the expression

$$tw = 1.3\frac{2z}{v}$$

where the maximum depth and minimum velocity likely to be encountered are used. The above expression increases the estimated time by 30% to allow for uncertainties in velocity and depth variations. If no information is available on the electrical properties of the study area, a first estimate will be obtaining from tables in function of the porosity and moisture content of the predominant lithology.

Sampling interval – One of the parameters utilised in designing radar data acquisition is the time interval between points on a recorded waveform. The sampling interval is controlled by the Nyquist sampling concept and should be at most half the period of the highest frequency signal in the record. Nevertheless, for good survey design, the sampling rate should be approximately six times the centre frequency of the antenna being utilised. The function relationship is

$$t = \frac{1000}{6f}$$

where f is the centre frequency in MHz and t is time in ns.

In some instances it may be possible to increase the sampling interval slightly beyond what is quoted, but this should one be done when data volume and speed of acquisition are at a premium over integrity of the data.

Antenna separation – Most GPR systems adopt separate antennas for transmitting and receiving (commonly referred to as bistatic operation). The ability to vary the antenna spacing can be a powerful aids in optimising the system for specific types of target detection. To maximise target coupling, antennas should be spared such that the refraction focusing peak in the transmitter and receiver patterns point to the common depth to be investigated. Increasing the antenna separation also increases the reflectivity of flat lying planar targets that can sometimes be advantageous.

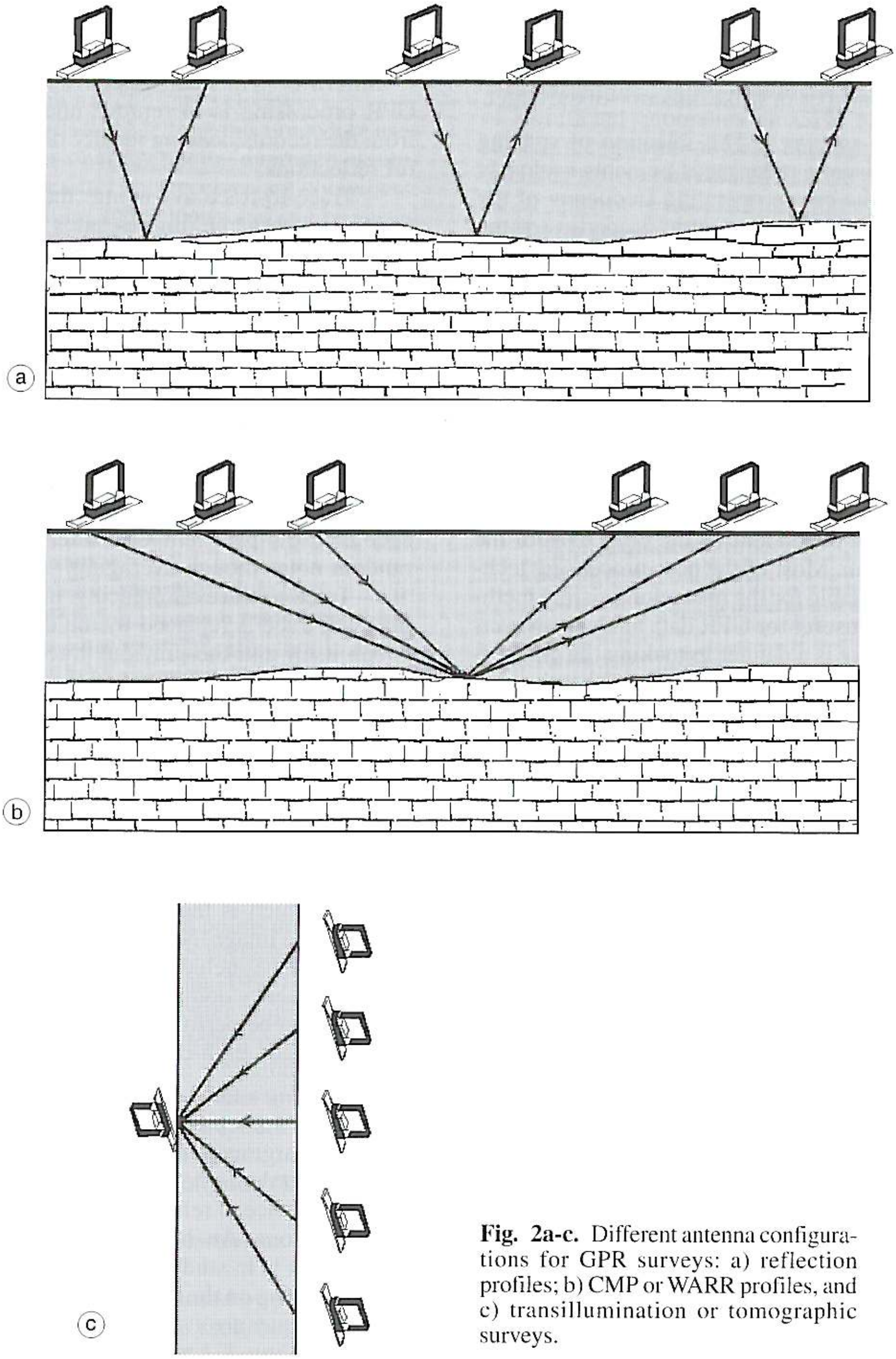

Fig. 2a-c. Different antenna configurations for GPR surveys: a) reflection profiles; b) CMP or WARR profiles, and c) transillumination or tomographic surveys.

Antenna orientation – In general, the antennas used for GPR are dipolar and radiate with a preferred polarity. The antennas are normally oriented so that the electric field is polarised parallel to the long axis or strike direction of the target.

Station spacing – The selection of spacing between discrete radar measurements is closely linked to the centre operating frequency of the antennas and to the dielectric properties of the subsurface materials involved. In order to assure the ground response is not spatially aliased, the Nyquist sampling intervals should not be exceeded.

4. Post-acquisition processing and interpretation

The degree of post-acquisition processing of GPR data is dependent on the objectives of the investigation. Most of the post-processing techniques available for the reflection seismic method are also useful for GPR data analysis. Nevertheless, there is a danger in making the comparison of radargrams to seismograms that the vector nature of radar may be overlooked, so incorrect assumptions are made about the way the radiowaves behave in geologic media. While seismic data processing can be used effectively in most cases, the electromagnetic polarisable characteristics of the radiowaves are analogous to seismic S-waves than to P-waves. The main post-processing and interpretation techniques are:

Gain recovery – When radar waves propagate into the subsurface by way of transmission, reflection and refraction, its electromagnetic energy is severely attenuated not only by spatial spreading but also by the Earth's conductivity. Consequently, the amplitude of the signal is much smaller in the later time. Gain recovery is designed to rescue this time dependent attenuation. There are several mathematical gain procedures:

– AGC (Automatic Gain Control) attempts to equalise all signals by applying a gain, which is inversely proportional to the signal strength. This type of gain is most useful for defining continuity of reflecting events.

– SEC (Spreading and Exponential Compensation) is a composite of a linear and an exponential time gain.

Filtering – The main objective of filtering in GPR processing is to remove undesired noise from the records, leaving ideally only meaningful reflections.

– Trace-to-trace averaging: this processing option, as the name implies, adds two or more traces to produce an average trace (moving average). The primary purpose of this type of processing is to emphasise flat lying or slowly dipping reflectors while suppressing rapidly changing ones acting as a spatial low pass filtering.

– Down-to-trace averaging: this option performs signal averaging by replacing the data at a given point by the average over a window centred about that point. This type of averaging acts as a low pass temporal filter by reducing random noise though averaging.

– Trace-to-trace differencing: in this processing each trace is replaced by the difference between itself and the previous trace (except for the first trace). This filter has the effect of enhancing rapidly changing features in the profile and suppressing flat lying or constant features. This filter is a simple high spatial filter.

– Delete mean trace: this filter is used to eliminate *ringing* and horizontal multiples from the radar image. When applied, this filter calculates a mean trace in time domain over a selected area, which is then subtracted from all the traces in the image. Normally a large number of traces must be included.

– Frequency domain filtering: three kinds of filtering can be performed in the frequency domain: low-cut, high-cut and band-pass filtering.

Modelling – GPR analysis is greatly assisted by forward modelling in which theoretical (synthetic) radargrams are constructed for layered models in order to derive insight into the physical significance of reflection events contained in radar sections. An important use of synthetic radargrams is in studying the effect of changes in the layering on the record. Three main modelling techniques are available: 1D modelling, raypath modelling, F-k modelling. Where the structure and/or horizontal velocity variations are complicated, iterative ray tracing may be used to determine a model that is compatible with the radar observations. The usual assumption is that reflections mark the boundaries between layers, each of which has constant velocity.

a) Zero offset modelling: this procedure uses a two-dimensional ray tracing approach assuming the transmitter and receiver are coincident. Both attenuation and velocity and can be varied in any zone. The model allows variable surface topography and incorporates the antenna pattern. This model does not address diffraction and evanescent wave features as well as multiple reflections.

b) Finite offset modelling: as in the previous case, this procedure also uses a two-dimensional ray tracing approach but permits any transmitter/receiver separation (Cai and McMechan, 1995). Figure 3a,b shows a two-dimensional layered modelling and their corresponding theoretical radargram.

F-k modelling: this procedure uses a two-dimensional Fourier approach transform single or continuous lines of point reflectors in a uniform velocity, zero attenuation background into the equivalent time-position radar section. This model fully incorporates diffraction events (Zeng *et al.*, 1995).

Migration – The purpose of migration is to transform GPR waveforms into an accurate picture of subsurface geology. As in the reflection seismic method, GPR profiles are migrated because subsurface reflecting points do not necessarily lie vertically beneath surface observation points (Bitri and Grandjean, 1998). An operational definition of computer migration is: a space and time variant filtering process which maps observed space-time amplitude data into either time or depth with correct amplitudes at true spatial positions. Figure 3c,d shows the effect of velocity in migration.

The main reasons for migrate GPR profiles are:

– Correct structural placement of dipping events.

– Focus diffractions caused by point scattering centres and subsurface fault bounds.

– Correct amplitudes for geometric focusing effects and spatial smearing.

– Sorting out of crossing events like those produced by sharp synclines.

– Improvement in resolution.

Stratigraphic interpretation – Identification of significant anomalies on GPR records is a pattern recognition process that consist of recognising reflection features that are characteristic of specific geological environment are essential for interpreting the radar images. In analogy to seismic facies, radar facies is defined as the sum of all characteristics of a reflection pattern produced by a specific formation (van Overmeren, 1998). Thus radar facies refers to differences in appearance of a radargram and radar reflections respond to both structural and textural features. These effects, called radar facies elements are:

- Reflection amplitude.
- Dominant frequency.
- Reflection configuration.
- Reflection continuity.
- External form (geometry) of radar facies unit.
- Reflection polarity.
- Abundance of reflections.
- Presence of diffractions.
- Degree of penetration.

Time slices – 3D GPR data can be considered as volume and therefore can be sliced in various ways. The data sliced horizontally provides time slices that allows the interpreter to generate amplitude contour maps with considerable ease and accuracy (Seren, 1998). Some interactive software packages enables to interpret effectively and efficiently 3D radar data.

5. Applications and case histories

Ground penetrating radar has been demonstrated to be a valuable tool in groundwater studies (Beres and Hasni, 1991), hazardous waste investigations (Brewster and Annan, 1994), mapping sediment sequences (Smith and Jol, 1997) and many other applications. The following case histories describe some other successful uses of ground penetrating radar in different subsurface reconnaissance surveys carried out by the author.

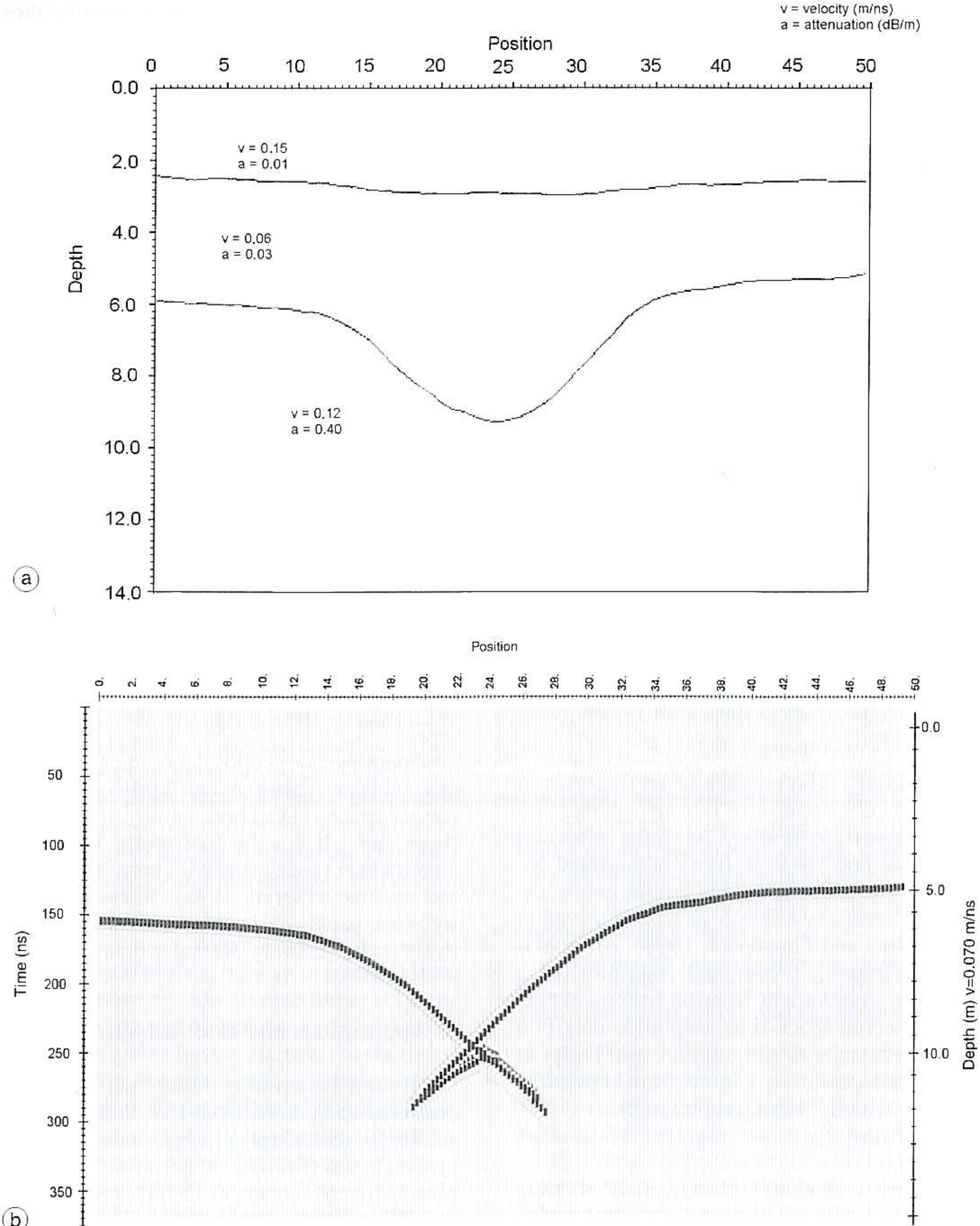

Fig. 3a,b. Example of 2D ray-tracing modelling program and the effect of unmigrated and migrated sections: a) model depicting a sharp synclinal feature in a reflecting interface; b) the resultant «bow-tie» shape of the multiple-branch reflection event on the non-migrated radargram.

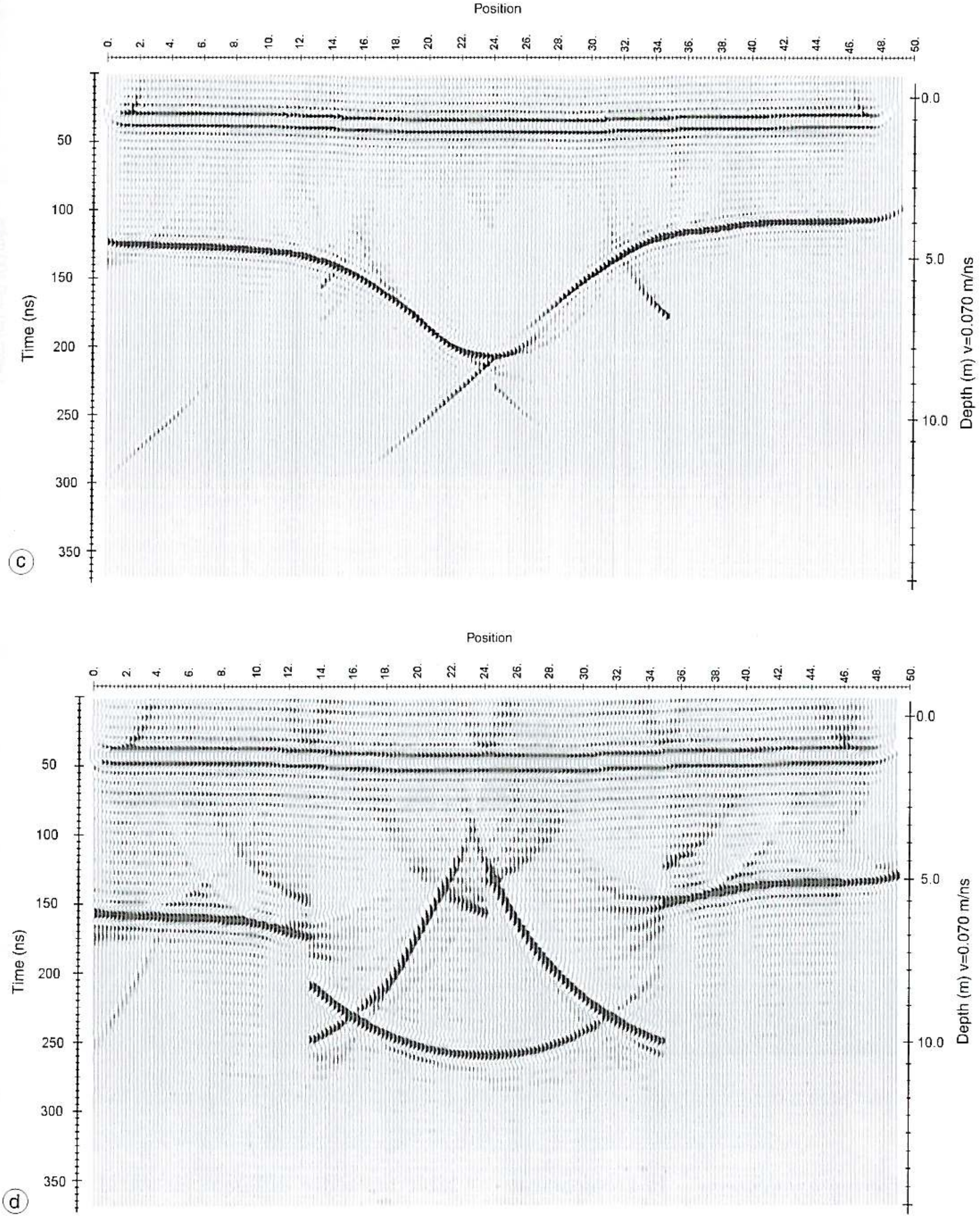

Fig. 3c,d. Example of 2D ray-tracing modelling program and the effect of unmigrated and migrated sections: c) the same radar section of fig. 3b, after migration using a correct velocity; d) the same radar section after migration using an overestimate velocity showing characteristic *smiles*.

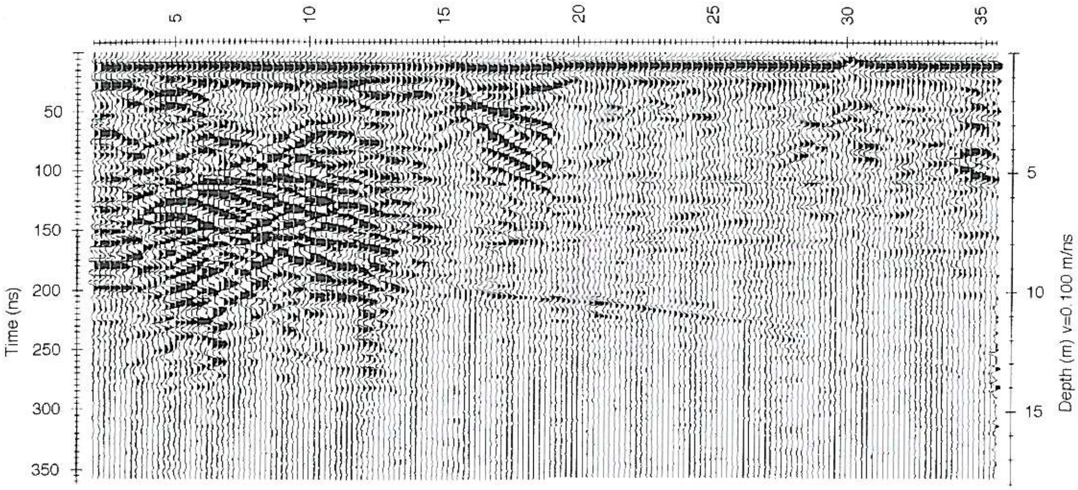

Fig. 4. A 100 MHz GPR profile recorded over karst cavities in Portocristo displaying distinctive high reflective hyperbolas.

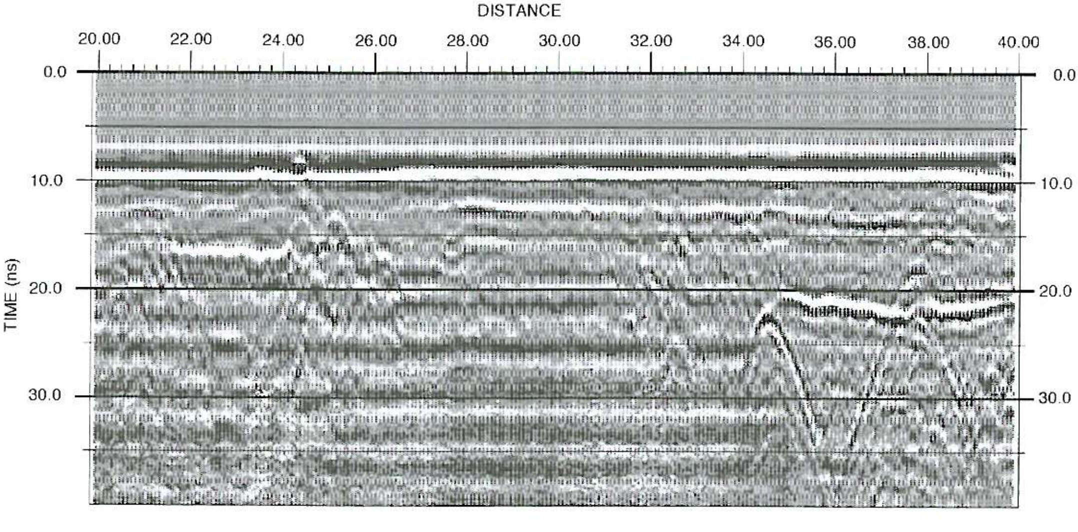

Fig. 5. Radar profile over buried pipes at different depths and positions depicting the typical hyperbolic signal.

Engineering applications – In geotechnical applications, GPR can be used to detect disturbed soils and backfills as well as to locate void and delaminations beneath concrete structures, *e.g.*, bridge decks, highways, and airport pavements (Benson, 1995). These objects exhibit markedly different electrical properties compared to surrounding materials. An example of a radargram acquired over a karst cavity in Portocristo (Mallorca, Spain) where a hotel was planned to be built is given in fig. 4. GPR suggested the presence of two overlaping shal-

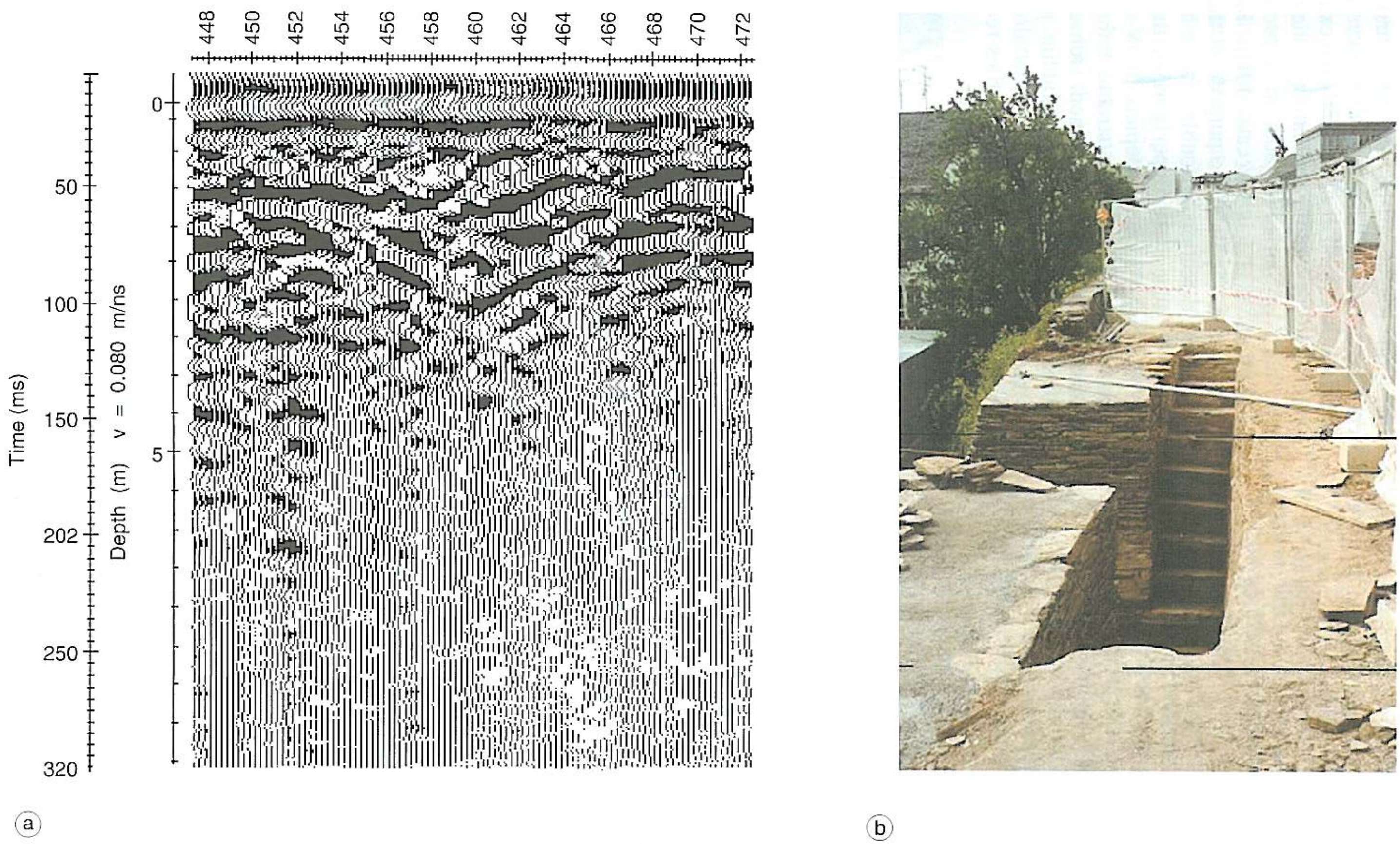

Fig. 6a,b. a) GPR record showing a V shaped anomaly generated by the buried Imperial Roman steps at the Lugo Wall; b) Imperial Roman steps found after digging on the places where V-shaped GPR anomalies were detected over the Lugo Wall.

low voids corresponding with strong hyperbolic reflections that were confirmed by drilling (Casas *et al.*, 1999).

Conduit and pipe detection – GPR is frequently used to locate features such as buried tanks and pipes (Zeng and McMechan, 1997), reinforcing rot in concrete structures, and conduits embedded in the ground for water, sewer, electrical cable or gas connections (Hayakawa and Kawanaka, 1998). Locating underground pipes for efficient pipe system management and for avoiding damage during excavation has become a relevant issue in metropolitan areas. The increasing use of trenchless techniques for underground pipe laying has opened a new field for the applications of ground penetrating radar. Before the drilling begins, the geological conditions and the positions of existing utilities have to be known because otherwise they could be damaged or destroyed. Most horizontal drilling projects in urban areas take place within a depth of 3 m, but as the available maps are not accurate, GPR can assist the horizontal drilling technique by predicting obstacles and avoiding damages. A good example of a radargram showing the effectiveness of GPR as a predicting tool in advance horizontal drilling in Valencia (Spain) is shown in fig. 5.

Road inspection practice – In recent years, GPR inspection of roads has evolved as a powerful technique offering several advantages when compared to traditional methods. In particular it is non-destructive, the results are quasi-continuous and data can be acquired at high rates (Davis *et al.*, 1994). Traffic obstructions can be minimised or avoided. Important applications are the inspection of pavement layer thickness and pavement damages, the investigation of sub-pavement structures and locating reinforcement bars and damage in concrete structures such as bridges. The comparison between two data sets obtained before and after rehabilitation work suggests the suitability of GPR as a tool for quality control.

Archaeological applications – Radar has many applications in archaeological no-dig investigations, especially as the depth of penetration required is usually small, commonly less than 3 m. Radar can be used as a first-look technique or as a fill-in method between areas of excavation (Imai *et al.*, 1987). One example of a GPR survey for determination of the depth and shape of buried objects in a protected archaeological site is the case of the Roman Wall of Lugo (Spain). The purpose of the survey was the detection of double-branch imperial steps to access the upper part of the wall from the city. Figure 6a depicts the V-shaped anomaly generated by the structure that was confirmed through the subsequent archaeological digging shown in fig. 6b. This pattern was used to detect many other steps along the more than four kilometers of profiles recorded (Casas *et al.*, 1997).

6. Conclusions

The nature of the radar method offers a number of advantages over other geophysical methods. The continuous vertical profile produced by the GPR method permits much more data to be gathered along a transverse, thereby providing a substantial increase in detail.

The primary reasons for the popularity of the radar method are its picture-like format of the anomalous features that allows an interpretation relatively forward if site conditions are simple and a strong dielectric contrast exists between the structure of interest and the surrounding material.

The major limitation of the method is the difficulty in distinguishing between significant reflections and extraneous reverberations, multiples, noise, diffractions, off-section ghosts, etc., make the interpretation of radargrams difficult in some cases. Therefore, considerable art often is needed to extract the desired information from the unwanted reflection patterns.

Another drawback is the limited penetration, especially in highly conductive ground. Depth of penetration is highly site-specific and measurements done on high loss ground often do not reveal the embedded structures.

Antenna ringing is commonly present on radar records and this effect hides the anomalies of targets. The ringing of unmatched antennas is caused by the fact that the antenna itself reacts to the electromagnetic wave that is supposed. Also, imperfectly shielded antennas catch reflections and diffractions from objects above the ground surface (trees, cars, etc.) and may mislead to interpretation.

Finally, a radar system is a complex and expensive instrument. The results of a radar survey depend on many interacting system controls, various field procedures, site conditions and data interpretation. Therefore, GPR cannot be considered as a magic rod and the successful application of the radar method requires personnel with an understanding of electronics, physics and Earth sciences.

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