PACS №: 41.20.Jb

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Application of Ground Penetrating Radar to Civil and Geotechnical Engineering

Contents

Abstract

Ground Penetrating Radar (GPR) is an imaging technique that uses wide-band nonsinusoidal electromagnetic waves to produce high-resolution images of the subsurface typically from 0-–10 m depth. GPR is an effective tool for subsurface inspection and quality control on engineering construction projects. The survey method is rapid, nondestructive and noninvasive. GPR has been successfully applied to a very wide range of tasks ranging from mapping geological structures, to identifying defects in concrete.

1. Introduction

GPR is a subsurface imaging method that provides high-resolution information to a depth of typically 0–10 m, although depths up to 40 m (Franke & Yelf 2003, Jol 2003, Bakker 2004) are possible in some geological environments. GPR was first put to practical use in the 1970's for ice sounding in Antarctica and has since gained wide acceptance internationally. The technique is nondestructive and noninvasive, utilizing low-power nonsinusoidal electromagnetic waves with frequencies ranging from 10 MHz to 4 GHz. GPR may be applied to a wide range of inspection tasks, for example to detect buried services (pipes, cables), for inspection of layering in roads and railway ballast, or for detailed mapping of steel reinforcing in concrete structures.

There are two main types of GPR, which are classified according to the type of transmitted signal (Figs 1 a,b). Impulse (or pulse) radar systems are the most widely used type and operate by transmitting numerous small pulses (typically 50,000-–100,00 pulses per second) of short duration (typically 1–10 nanoseconds) nonsinusoidal wide-band radio energy. Pulse GPR systems are easier to manufacture and hence lower cost; however they are normally limited by the mean signal power that can be transmitted. Another less commonly used type of GPR is the Continuous Wave (CW-GPR) method, which uses sinusoidal radio waves of a single frequency. A more advanced form of CW-GPR is the Step Frequency (SF-GPR) method, which use multiple steps of discrete frequencies, which are progressively incremented across a broad frequency spectrum in a programmed step-wise fashion. These CW systems can transmit more mean power, however a much higher level of signal processing is required to convert the raw data back into a form interpretable by the operator.

Almost all commercial GPR systems use voltage-driven dipole antennae. In order to achieve greater penetration depths, we are currently investigating the potential to use current-driven antenna (Harmuth 1990). These have the potential to achieve a kilometre of depth penetration in rock when used in an array configuration.

GPR can either be used in reflection or transmission modes. The Reflection Profiling Survey method is the most common and is normally conducted using two antennae (called the bi-static mode), with a separate transmitter (Tx) and receiver (Rx) as shown Figure 2a. These antennae are placed directly on, or relatively close to, the ground surface to be measured. The antennae may also be mounted on a wheeled trolley or sled to protect the equipment and to speed up the survey.

The physical size of the antennae varies considerably from about 100 mm (1.5 GHz) for concrete inspection, to 3 m (25 MHz) for deeper geological applications. For the higher frequency antennae, the Tx and Rx are normally combined inside one box called a transducer.

Radio reflections from targets in the ground are detected by the receiver unit, amplified and displayed by the control unit. Reflections occur where there is a change in the dielectric properties of two adjacent layers across a soil boundary, or a material interface. Subsurface velocity information (and hence depth) can be derived by progressively separating the Tx or Rx from each other while recording the delay in the arrival of signals; this is called the Wide Angle Reflection and Refraction (WARR) method (Annan 1985) (Fig. 2b). Various arrays of multiple offset antennae may also be used to derive layer properties such as the dielectric constant (and hence velocity and depth) in real time and also to improve subsurface resolution (Fig 2c).

Velocity information is also commonly derived by the analysis of the shape of hyperbolic reflections from subsurface targets such as pipes or cables. This is conducted during data processing by matching the shape of a hyperbolic curve to that of a hyperbola in the data. The derived value is used to establish the correct depths and to focus the diffractions from subsurface objects back to their correct geometric shapes. This process is called migration.

Where space is limited, the Tx and Rx antennae may also be combined into a single unit (called mono-static mode), although this mode does not allow detection of shallow targets located close to the antenna due to saturation of the early signal arrivals by the decaying Tx signal.

For fast surveys of highways where it is impractical to have an antenna in contact with the road surface, then air launched (or horn) antennae are used. These antennae operate at frequencies in the range 1–2 GHz and are typically mounted at a height of approx. 400 mm from the surface on the front or rear of a vehicle. Horn antennae provide images of the shallow pavement layers up to about 500 mm depth. The thinnest pavement layer that can be resolved using a 2 GHz horn antenna is approximately 25 mm. For railway surveys, 1 GHz horn antenna have been used to image ballast condition to depths of approx 750 mm.

Borehole radar (BH-GPR) shown in Figure 3 requires special waterproof antennae inserted into boreholes and suspended by cables on a winch system. For inclined boreholes fibreglass rods are used to push the antennae into the BH. The borehole must be uncased, or cased with PVC casing. (Metal casing prevents the BH-GPR method being used). Two borehole measurement modes are commonly used. The BH Reflection Profiling mode (Fig. 3a) requires only a single borehole, with the Tx and Rx being raised or lowered at a fixed separation distance while reflections of electromagnetic waves occurring at joints in the surrounding rock, or at lithologic boundaries,

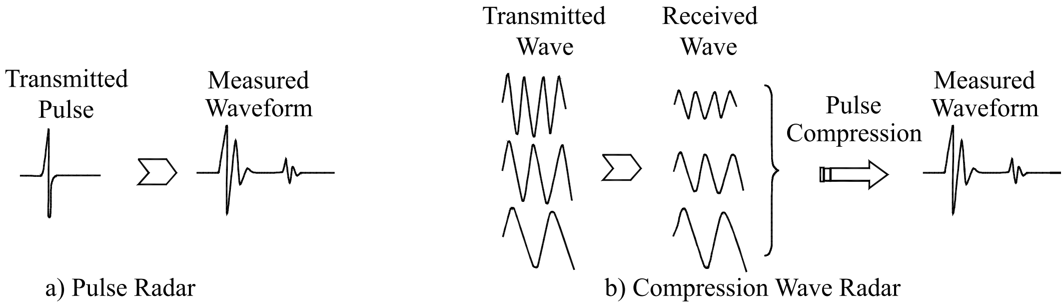


Fig. 1. Schematic Diagrams of Pulse Radar and Continuous Wave Radar.

are recorded. When more than one BH is available at the site, then the BH Transmission mode can be used to obtain either a Cross Hole measurement, or a more detailed Tomographic Profile of the rock mass between the holes (Figures 3b and Fig 3c).

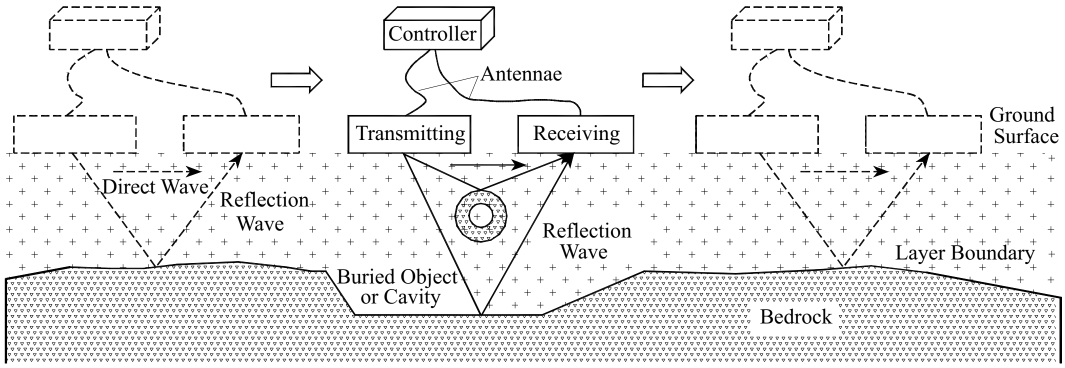
For transmission measurements, normally the position of the Tx antenna is fixed at a given depth in the BH, while the Rx antenna is moved in the adjacent BH (Fig 3b). The position of the Tx is then raised or lowered to the next recording position, and the process repeated successively to provide full ray-path tomographic coverage of the intermediate rock. Variations in the radar signal travel time through the rock and usually also the amplitude of the received signal are recorded and used to reconstruct an image of the anomaly. Alternatively the Tx and Rx can be simultaneously lowered or raised together in parallel to obtain an image of geological anomalies that lie between the two BHs. This type of Cross Hole method is more rapid, but does not provide the same detail of the 3-D structure as the full tomographic method.

2. Appropriate Application Targets

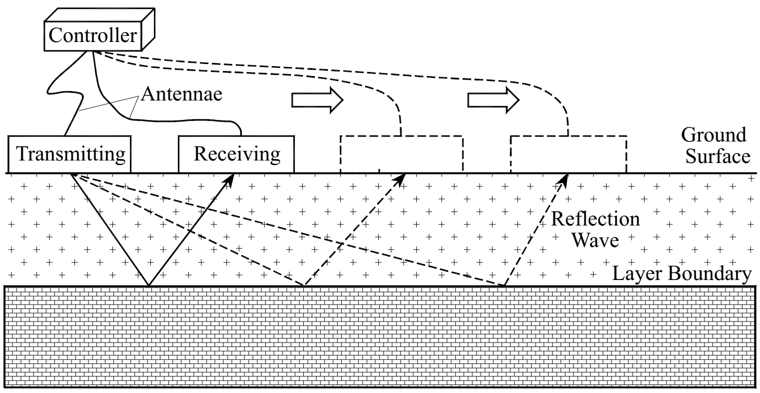
The applications GPR are very varied and include the location of buried services, the detection voids or cavities, mapping bedrock depth or faults and fracture zones in rock. Other applications include locating steel reinforcing in concrete, geotechnical foundation investigations, archaeological, environmental and hydrogeological surveys.

GPR is an effective tool for subsurface inspection and quality control on engineering construction projects. The numerous applications of GPR include the following:

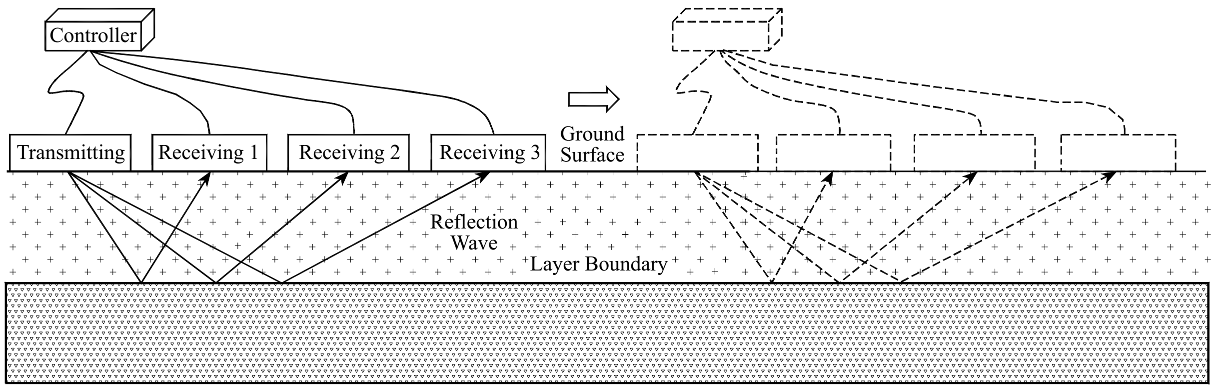
1. Mapping pipes (including PVC pipes), cables and other buried objects.
2. Continuous inspection of layers in road pavements and airport runways. Due to the rapid data acquisition rates, it can be used at highway speeds to monitor changes in subgrade and asphalt pavement layers.
3. Mapping cavities or voids beneath road pavements, runways or behind tunnel linings.
4. To monitor the condition of railway ballast, and detect zones of clay fouling leading to track instability.
5. Detailed inspection of concrete structures, location of steel reinforcing bars and pre- and post-tensioned stressing ducts. GPR can be used in 3-D mode to map multiple layers of steel in buildings, in order to avoid damage when drilling through such structures.
6. Inspection and quality control of pre-cast concrete structures, such as bridge deck beams.
7. Detection of zones of honeycombing, voiding and chloride attack in concrete.
8. Mapping zones of deterioration and delamination on bridge decks.
9. Mapping zones of termite attack or fungal decay in trees or timber structures, such as wooden bridge beams.
10. Mapping soil, rock or fill layers in geological and geotechnical investigations, or for foundation design.
11. BH-GPR is used to detect faults and for determining the degree of fracturing of the rock mass (e.g. for investigating the structural integrity of pillars, or nuclear waste repository zones).
12. Mapping bedrock and excavation conditions along proposed cable or pipeline excavations.
13. Mapping detailed sedimentary stratigraphy, both on land and beneath rivers and lakes, particularly for pipeline crossings. (GPR will penetrate through fresh water, but is rapidly attenuated by salt water).
14. Mapping snow and ice thickness on glaciers, location of ice-core holes for climate change measurements.



(a) Measurement of a 2D GPR Profile using constant-offset Tx and Rx antennae.



(b) Wide Angle Velocity Measurement.



(c) Measurement of dielectric values using array of multi-offset receivers.

Fig. 2.

15. Mapping buried archaeological ruins.

16. Detection of unmarked graves in forensic studies and the location of bodies buried in snow avalanches.

17. Mapping buried unexploded ordnance (such as relict bombs) at proposed construction sites.

Developments of 3-D imaging techniques and low frequency radar systems are increasing the penetration depth of GPR and expanding the range of applications in the following areas:

18. Investigating active geological faults. 3-D time slices enable visualization of these complex targets.

19. Surveying sediments beneath the bottom of rivers and lakes. New low frequency (10-–50 MHz) high-powered antennae have been used to map ground structures even in semibrackish coastal areas.

20. Hydrogeological and glaciological investigations, and monitoring the spread of hydrocarbon contamination in the ground.

At sites with very conductive zones (such as clay-rich soils after rainfall, salt marshes and some saturated waste disposal sites), the received radar

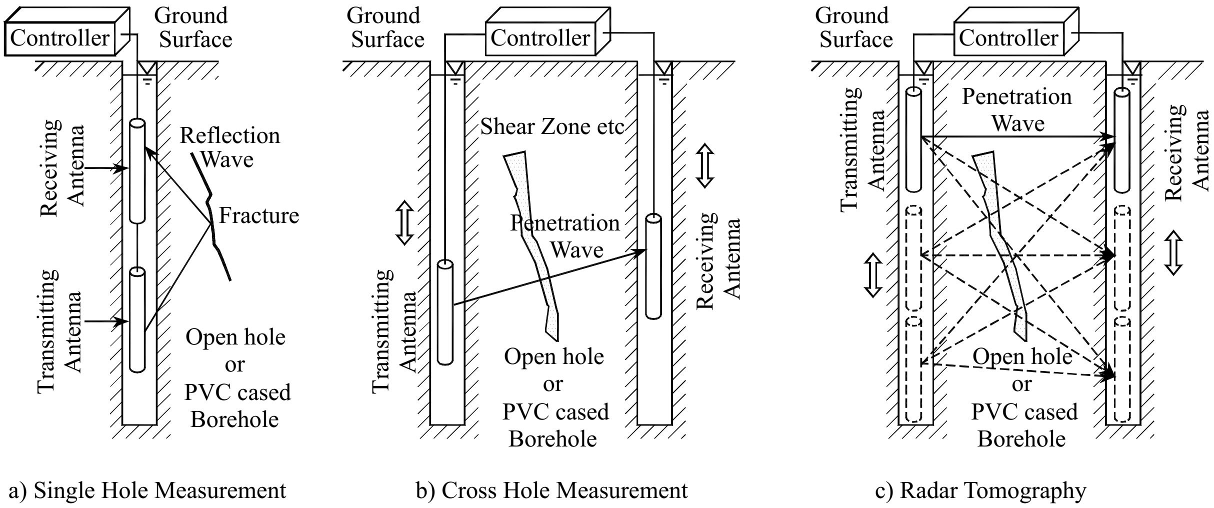


Fig. 3. Measurement Variations with Borehole Radar.

signals may be too weak to obtain adequate survey results. In such places it is recommended to use alternative geophysical methods, such as multichannel resistivity surveys.

3. Planning of GPR Surveys

3.1. Review of existing material

The feasibility of using GPR and the outcomes of a proposed survey can often be predicted by studying existing site information and by site reconnaissance visit. Survey planning is conducted with due consideration for the expected subsurface material properties, the nature and depth of the targets and possible limitations in access for the equipment.

The key features of GPR are that it provides a continuous record of the subsurface and has much higher spatial resolution than other geophysical methods, such as seismic and electrical surveys. However, if the site conditions are unfavourable (e.g. wet clay soils), then GPR may have shallower penetration depths than other methods. Therefore planning of GPR surveys is crucial to obtain a successful outcome.

In the USA, Ground-Penetrating Radar Soil Suitability Maps have been produced by Doolittle et al (2004) which show the likely success of conducting GPR surveys in all states. These maps are based on the USDA-Natural Resources Conservation Service soil classification maps, and are available on line.

It is highly advisable to conduct a reconnaissance visit to the survey site prior to conducting a GPR survey. For mapping buried services, it is recommended to obtain plans of existing buried utilities and man-made objects from local municipal authorities. The local soil types should be evaluated for clay content, generally radar works welkl in dry soils with low conductivities.

Metal objects such as electric cables for power lines, anchoring rock bolts, wire nets in cement mortar and bracing supports inside walls and tunnels may interfere with the GPR survey data and complicate the interpretation of survey results. It is important to note the locations of such objects prior to conducting the GPR survey and also to mark their exact location on the radargrams during the survey. This facilitates interpretation considerably and helps to avoid incorrect conclusions. It is important to distinguish between spurious “air-wave” reflections caused by above-ground objects (e.g.: metal lamp posts, motor vehicles, mesh wire fences, overhead cables, etc), which typically cause wide limbed hyperbolic reflections on the radargrams, from genuine below ground reflectors, which have typically have steeper limbed hyperbolic reflectors.

3.2. Choice of transmitting frequency

The centre frequencies of commercial GPR antennae typically range from 25 MHz to 4 GHz. Generally there is a direct relationship between the transmitter frequency (determining the wavelength) and the resolution that can be obtained. Conversely, there is an inverse relationship between frequency and penetration depth. High frequencies are used to detect small, shallow targets and low frequencies are used to detect larger, deeper targets. The following points need to be considered in choosing transmitting frequency.

1. Target properties (size, depth and composition). Metallic targets are good reflectors; PVC pipes generally produce much weaker signals. Some geological layers may be undetectable, especially

if they are thin, or have poor radio contrast with the adjacent layers.

2. Radio frequency properties of the soil, rock, or medium in which target is buried.

3. The required resolution of the target. Millimetre resolution is possible at 4 GHz, whereas only meter resolution may be obtainable at 25 MHz. With some GPR systems it is possible to record two or more frequencies simultaneously; this can provide both high resolution and deep penetration simultaneously in one recording pass, thus reducing the overall survey time and cost.

4. Presence of moisture and clays, which limit signal penetration.

5. Site topography, vegetation cover, access for the antenna and for vehicles pulling antenna (if applicable).

6. Weather conditions; generally better results are obtained with dry ground.

The penetration depth and the resolution obtained with GPR depend primarily on (1) the transmitting frequency of the antenna, (2) the electrical properties of the earth and (3) the contrasting electrical properties of the target. The main physical properties of interest are the Dielectric Constant and the Electrical Conductivity, as shown in Table 1. The higher the transmitting frequency used, the better the resolution of the target, but the shallower the penetration depth.

For optimum performance, the central transmitting frequency of the antenna needs to be matched for the site conditions, the depth of the target and the survey purposes. It is recommended to bring additional antennae of other frequencies (higher and lower frequencies) to the recording site because site conditions such as geology, or steel reinforcing patterns in concrete, are often different from those expected.

3.3. Arrangement of survey lines

For linear targets (such as buried pipes) the GPR survey lines are normally recorded perpendicularly to the longitudinal direction of the expected buried services, where possible. For metallic targets (e.g. pipes) the antenna are normally orientated with their diploes parallel to the long axis of the target, for non-metallic targets (e.g. gas pipes) the antenna dipoles are normally set parallel to the target axis. (This configuration exploits the polarization configuration of the targets). The survey line spacing varies according to target type, size and depth. It is typically between 0.25–1.0 m as a standard for civil engineering targets, but may be increased up to 10–20 m for mapping geological layers. The measurement interval between individual GPR waveforms is normally set between 1 cm and 1 m, depending on the size of the target and the resolution required. As an empirical rule, to define discrete targets such as pipes, it is necessary to record a minimum of 2.5 waveform traces in the distance that the diameter of the target occupies. Additional survey lines, or a multi-line grid, may be required to detect small or multiple targets, or in cases where a high degree of spatial accuracy in data analysis is necessary.

The layout of survey lines and line spacing are determined in consideration of the following points:

1. Antenna frequency.

2. Spatial resolution required to define the target.

3. Speed of moving the antenna.

4. Topographical, vegetative and geological conditions.

5. The time available for data acquisition.

6. The speed and accuracy of position tracking equipment (D-GPS).

7. The available budget for the survey.

8. Other conditions specific to the site.

For linear buried objects such as pipes and cables, the target is most clearly defined by recording the GPR survey lines at right angles to the orientation of the pipe. However for survey lines recorded on roads, it is normally required to orientate the direction of survey lines parallel to the direction of the road in order to avoid disrupting the traffic. In such case services buried along the direction of the road may not be detected with longitudinal GPR lines. On roads surveys it is strongly recommend where possible to record short transverse lines perpendicularly across the road at regular intervals while using traffic control, since these transverse lines will reveal the location of such longitudinal services.

When insufficient target definition is produced by widely spaced survey lines, then a detailed survey should be conducted using a grid of closely spaced lines. Spacing of these lines depends on the antenna frequency, but is typically 5 cm for 1.5 GHz, 25–50 cm for 400 MHz, and 1–2 m for 100 MHz antennae. For targets such as mapping steel in concrete structures, complex buried archaeological ruins, or estimating landfill thickness, then a dense grid mesh of survey lines recorded in two directions at right angles to each other may be used and the results processed to show three-dimensional shape of the targets. Horizontal sections through the ground (called ‘Depth Slices’) can be constructed using commercially available software; these are very useful for understanding the true layout of pipes and cables.

Table 1. Transmitting Frequency and Earth Electrical Properties Affecting GPR Surveys

GPR Parammeter	Dielectric Constant		Electrical Conductivity		Transmitter Frequency		Remark
	low	high	low	high	low	high	
Propagation Velocity	fast	slow					Velocity is high in materials such as dry sand, and slow in water-saturated materials.
Attenuation			low	high			Signal attenuation is influenced strongly by electrical conductivity at high frequencies.
Penetration Distance			low	short			The lower the attenuation, the greater the penetration distance.
Wavelength					long	short	Short wavelengths are normally used for concrete structures; long wavelengths are applied to mapping geological layers.
Resolution					low	high	The shorter wavelength, the higher resolution of subsurface targets.

3.4. Depth of investigation

The depth of the GPR survey depends on the transmitting frequency, the transmitted power and the conductivity of the ground or medium investigated. Depth range varies from 25 mm to 40 m, but is typically 0.1–5 m for most geotechnical applications. Deeper penetration is possible with lower frequencies (e.g. 25–100 MHz), providing that the ground is not too conductive.

Most GPR surveys in civil engineering are conducted with frequency range between 1.5 GHz and 400 MHz, for which the penetration depth is typically between 0.3–2 m. Table 1 shows that a combination of a low transmitting frequency and resistive ground can increase the penetration depth.

Below the groundwater level it may be difficult to obtain sufficient signal penetration. In highly conductive zones, such as saturated montmorillonite clays or saline marshes, it is almost impossible to obtain useful results below 1–2 wavelengths of the antenna. Not all clay types are unsuitable for conducting GPR surveys. Kaolinite clays derived from weathered granites generally give reasonable results, whereas montmorillonite clays derived from weathered basalts have much higher signal attenuation rates.

Under good conditions GPR systems with a frequency range below 100 MHz can obtain penetration depths in excess of 10 meters. In dry crystalline rock (e.g. granites) penetration distances of more than 100 m are possible at 25–50 MHz.

4. Conducting Field GPR Measurements

4.1. Equipment required

GPR equipment is chosen in consideration of the objectives of the survey, particularly the depth of the target, the accuracy required and the project budget.

GPR equipment normally consists of a power source (either internal rechargeable battery, or external 12 volt battery or mains A.C.), a control unit, a display screen, antenna and inter-connecting cables. As discussed above, the correct selection of antenna frequency is critical for success of the survey.

GPR equipment price generally reflects the number of functions the system can perform. Smaller GPR systems are commonly dedicated to specific applications (such as shallow utility locating) and may not be suitable to conducting surveys on road pavements at highway speeds, or for connecting deep-penetration high powered antennae. Signal quality, the signal jitter and time base stability varies considerably between manufacturers.

4.2. Preparation for the GPR survey

1. When the survey area is on a public road or park, closure permits may be required in advance from the relevant authorities.

2. The locations of the survey lines are marked out at the site. These are normally painted on the

ground or marked with chalk. The start and end positions of each survey line are recorded on field data sheets and marked on a site plan.

3. The antennae are mounted on a sled or wheeled trolley to enable them to be pulled smoothly across the ground.

4. For ground-coupled antennae, best survey results are generally obtained with the GPR antenna placed close to the ground surface which should be as flat as possible. Grass at the site should be mown short and bushes or shrubs along the survey route should are cut away where practical.

5. On sites with rough ground the surface may require smoothing with a bulldozer or grader to allow good contact between the base of the antenna and the ground surface. This is mainly applicable on large scale geotechnical projects.

Permits for the survey are obtained from the relevant landowners, local community and authorities. Due to FCC regulations, it may be required to register the intended use of the antenna.

The survey lines are usually laid at the site using simple survey equipment such as measuring tapes. A site plan with an appropriate scale makes this operation easier. Features such as roads, utilities, buildings, topography and vegetation should be noted. For larger projects, differential GPS or laser positioning equipment is commonly used for tracking the location of the survey lines. Base stations are set up at appropriate locations to facilitate this.

4.3. Field survey procedure

1. The GPR equipment is set up and connected to a power source, normally a 12 volt battery or an AC source (if available). Adequate time should be allowed for the equipment to warm up and achieve a stable zero time position. A preliminary test is conducted prior to the main survey in order to ensure the GPR system is functioning properly and to optimise the instrument settings. Recording time range (measured in nanoseconds), sampling rate, signal gains and band-pass filters are set according to target depth and antenna frequency. A distance measuring wheel (if fitted) should be calibrated on site against a known distance.

2. Relevant site information, including the detailed location of the GPR survey lines, variations in surface conditions, sources of spurious reflections from above-ground metal objects close to the survey line should be recorded in the field observer's logs to assist in interpretation.

3. Where required, the subsurface velocity is measured using the techniques illustrated in Figures 2b,c.

The equipment is set up so that the operator of the control unit can clearly see both the monitor screen and also the antennae during the survey. The antennae are normally mounted on a wheeled trolley or sled to facilitate their movement. The interconnecting cables between the control unit and the antennae are easily damaged. Care should be taken to avoid rough handling of these cables, due to snagging on obstructions, abrasion on rough surfaces, or by driving over them. Snap-on strain relief loops fitted to the both ends of the cables help to avoid pulling the cable out of the connectors. Plastic spiral wrap cable protection can be also added to the sections at the ends of the control cables to prevent damage from frequent tight bending. A spare set of cables should be taken to site when ever possible.

According to the type of the survey, the antennae are either moved by pulling them manually across the ground surface, or by towing with a vehicle. For manual pulling of the antennae, scan speeds of 20–100 scans per second are sufficient, for road or railway surveys with fast vehicle speeds the required scan rate is typically 200 scans per second or greater.

The propagation velocity of the electromagnetic waves in the earth typically varies in the range between 0.08–0.12 metres per nanosecond (m/ns). For many survey purposes, such as location of buried pipes, it may not be necessary to know the subsurface velocity very accurately and an approximate velocity value is sufficient to estimate the depth of the target. However postprocessing routines such as Migration do require accurate knowledge of the velocity. Velocity measurements therefore are recommended using techniques as illustrated in Figures 2b,c. Alternatively, the velocity can be obtained during postprocessing by analysis of the hyperbolic diffractions produced by discrete targets.

If construction equipment is available at the site, direct depth calibration by test pits excavated to expose structures detected with GPR enables the actual depths to the top of targets to be measured. These calibrated depths can then be used to estimate the depths other targets at that site under similar ground conditions. Coreholes drilled to measure the depth of steel reinforcing in concrete, or thickness of or asphalt layers on roads provides similar calibration data.

The velocity of the surface layer can also be determined quickly at the site using a portable dielectric meter (e.g. a Percometer), or determined in the laboratory using core samples and a network analyser.

If light rain occurs during the survey, recording can normally be completed providing adequate waterproof covering is provided for the survey equipment. It is advisable to manufacture waterproof plastic covers for the antennae that can easily be attached when required. Heavy rain may saturate the ground, adversely affecting GPR signals, and may cause failure to the survey equipment. Note that a variable moisture content across a site, or along a section of road, may result in inaccurate depth measurements unless the local moisture variations are included in the velocity calculations.

4.4. Assessment of measurement results

The quality of results acquired on site should be assessed during, or immediately after, the field survey by examining the GPR images displayed on the monitor screen. Where required, lines should be repeated to ensure the data is adequate to achieve the objectives of the survey.

The data needs to be critically reviewed at the site to check that it is of good quality and to eliminate sources of radio noise, or spurious airwave reflections from above-ground objects such as pedestrians or moving cars.

Sources of unwanted signal noise, or abnormal signals, should be identified and the causes removed where possible. Mobile phones or two-way radios may cause interference should not be operated close to the receiver during recording operations.

Well defined subsurface anomalies (pipes and cables) may be interpreted on site and marked directly on the ground using chalk, paint or survey pegs. More complex targets, for example archaeological ruins, may require signal processing which is normally conducted subsequently in the office.

4.5. Safety aspects

1. Risk factors related to on-site hazards should be assessed prior to commencing the fieldwork.

2. The average signal power transmitted by small commercial GPR systems is in the order of 1 milliwatt, which is approximately 600 times less than that transmitted by a mobile phone. Therefore the levels electromagnetic radiation produced by small commercial GPR transmitters are not considered a health risk to operating personnel.

During field survey operations, care needs to be taken prevent injury to the operators, or damage to the equipment and cables, especially when traffic or construction vehicles are moving around the site. Safe traffic control is required to avoid accidents during surveys on roads. Special care should be taken when conducting surveys on inclined slopes (e.g. scree slopes) or on high buildings to prevent injuries from falling or rolling. Working underground in confined spaces, such as sewers, may require special procedures. Operations in confined spaces with high methane levels may present a risk from gas explosions, or poisoning from noxious gases. Prior to operation at sites, the GPR equipment may require safety inspection from regulatory staff to ensure it complies with local safety standards, especially with regard to gas explosion risk.

In order to avoid accidents during GPR surveys on public roads it is recommended to arrange traffic controllers, plus speed control signs and barriers. At night reflective barriers should be used and the operators should wear appropriate reflective clothing. Flashing lights and reflective tape may also be attached to the antennae. For continuous surveys along busy roads, guard cars with flashing signs may be required to protect the operators and equipment.

The averaged transmitted power density levels of small commercial GPR systems are less than 0.0001 W/m^2 at 5 cm. This is approximately 1,000,000 times below the critical 10 mW/cm^2 (100 W/m^2) levels established by the United Sates Occupational Health and Safety Administration (OHSA). Therefore the levels of electromagnetic radiation produced by small commercial GPR transmitters are not considered a health risk to operating personnel.

The transmitted power levels also do not generally cause significant interference to other electronic equipment.

5. Data Processing

5.1. Production of survey location plan

A survey location plan at an appropriate scale is normally produced showing the layout of the GPR lines and relative locations of pertinent site features.

The site plan should include a scale, north direction and clearly show the layout of the GPR survey lines. Interpreted features may be marked on the plan as appropriate. The coordinate positions of utilities detected with GPR should be measured with a survey tape, or recorded using differential GPS or a total station theodolite and plotted as a CAD drawing if required. Sketches and photos of the site are also very useful for interpreting the survey results.

5.2. Production of GPR sections

To enable analysis and interpretation the GPR results, the profiles are normally displayed as 2-D time sections, or as depth sections if the propagation velocity is known. Digital signal processing is applied to the data as required. This varies according to each survey, but normally involves filtering to remove unwanted noise, gain adjustment to balance signal strengths, migration to remove diffraction effects, corrections for variations in surface topographic elevation and graphic display using various colour palettes or wiggle-trace formats.

The GPR profile (or 'radargram') is displayed on screen or printed out for each survey line. The interpretation of a 2-D survey section is based on these profile sections. In many cases the raw GPR data is adequate for the interpretation to be conducted. For more complex targets and deeper layers, geophysical processing is applied using similar techniques to those used in shallow seismic reflection surveys.

GPR processing routines vary per site and according to the type of equipment used, and may include the following:

1. Adjustment of Time Zero position [33].
2. Band-pass filtering (to remove unwanted high or low frequency noise or DC bias).
3. Stacking (if required) to improve the signal-to-noise ratio and to shorten long profiles so the entire line may be seen on one computer screen.
4. Moving average filtering (to smooth out jitter between waveforms).
5. Background removal via subtraction of mean trace or moving average window to remove constant horizontal noise bands (e.g. ringing) from the data.
6. Deconvolution filtering (to remove unwanted multiple echoes, or signal 'ringing').
7. Migration (to focus the hyperbolic diffractions from buried objects back to their true positions). (Yilmaz, 1987).
8. Gain to increase signal amplitude. This may be applied manually, or automatically using automatic gain control (AGC).
9. Conversion to depth sections and correction for variations in surface elevation.
10. Redatuming to remove distortion effects caused by layers with different velocities.
11. Construction of 3D sections.

For large projects, the data processing is commonly automated by writing macros and the processing conducted as a batch sequence. Prior to this, test processing is conducted on selected lines to optimise the processing routines. Usually the processed data is recorded digitally onto the hard disc of a personal computers, or stored on removable external media (CD-RW, DVD-RW, USB memory sticks). The GPR profiles are printed using standard printers or plotters.

GPR profiles are displayed using as following graphic modes:

1. Wiggle-trace waveforms (Fig 5a). This is the simplest display mode, but may be difficult to interpret.
2. Grey scale intensity. This mode is good for identifying structures in the ground, e.g. steel bars in concrete.
3. Colour palettes. These are used to display more subtle features, or highlight required targets or layers. Colour palettes may be user-customized to optimally display the required features, while removing unwanted visual clutter.

6. Data Analysis

1. GPR results are interpreted by recognizing diagnostic reflection patterns on the radargrams.
2. Discrete buried objects typically appear as hyperbolic reflections in the raw data, with the limbs of the hyperbolae projected downwards like an inverted "V" shape. These hyperbolic diffraction patterns can be converted back to their true shape and size by applying a signal processing routine called Migration.
3. Subsurface layers appear as continuous reflectors on the radargrams. These layers are normally digitised on screen and plotted as 2-D sections using commercially available graphical programs.
4. Where the data has been recorded as multiple lines on a grid, then the results can be processed and displayed as a 3-D plot, with time-slice sections made at user specified depths to show the relative orientations of subsurface targets.

Reflection patterns in the raw GPR profiles do not represent the true shape or orientation of subsurface objects. Discrete buried objects (e.g. pipes, cavities) typically appear as complex hyperbolic reflections in the raw data, whereas dipping layers appear as linear interfaces with shallower angles of dip than their true position in the ground, as shown in Figure 4. For simple targets that are widely spaced apart, these raw reflection patterns are normally adequate for interpretation by trained operators. For complex or closely spaced targets, signal processing is applied to improve the clarity and resolution of the radar images.

The true shape and orientation of the targets can be obtained by applying Migration routines, using velocity values measured in the field (as shown in

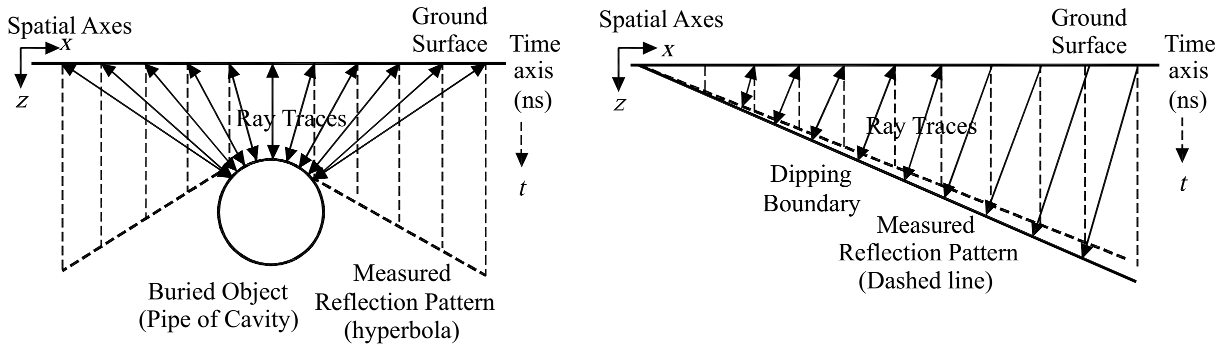


Fig. 4. Examples of different reflection patterns obtained from buried object (e.g. pipe or cavity) and from a dipping layer in the ground.

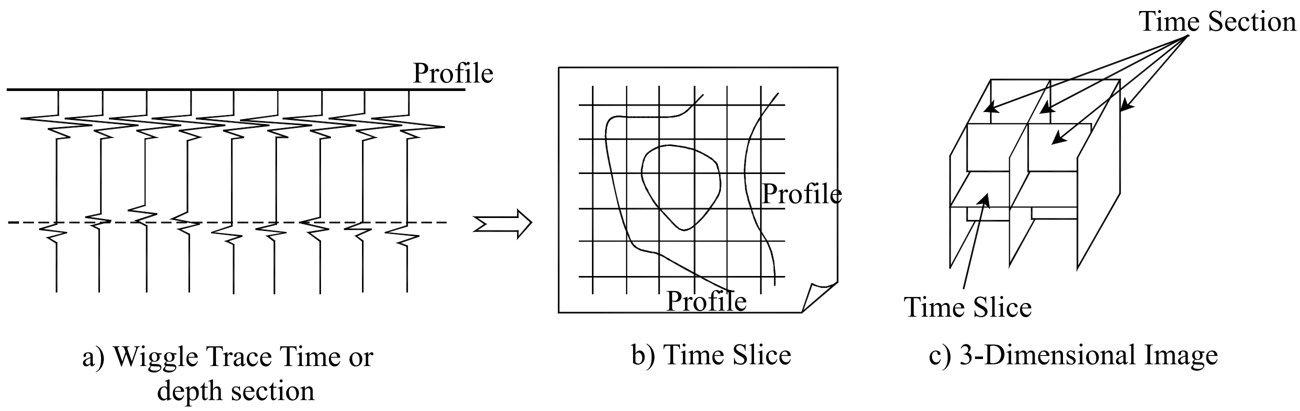


Fig. 5. Examples of various GPR Output Formats.

Fig 2), or calculated subsequently in the office using curve-fitting methods.

These curve-fitting routines are included in most commercial data processing packages. They calculate the average propagation velocity of the medium in which the target is buried by matching the shape of a hyperbola to the outline of the target reflection. Note that the velocity commonly gets slower with increasing depth (due to increased moisture content), therefore a velocity value calculated at e.g. 1.0 m depth may not be applicable to deeper targets. To overcome this, the velocity needs to be derived for all hyperbolae visible in the section and the appropriate velocity value applied to a target at a specific depth.

3-D data processing requires a dense layout of survey lines typically recorded at 0.25–1.0 m spacing. The processed data can be displayed as either Time Slices or Time Sections, as shown in Figures 5b,c. A Time Slice is a horizontal section through the ground at a given time range or depth. These plots display the absolute amplitude of signal reflections from buried targets and are often applied for archaeological and utility location surveys.

For locating steel reinforcing bars in concrete, small grids typically 0.6x0.6 m are recorded with survey lines running in both X and Y directions with typically 5 cm spacing between the lines. This survey method is useful prior to drilling through concrete floors or walls in buildings, to avoid hitting the steel stressing ducts or electrical cables. An example is shown in Figure 8.

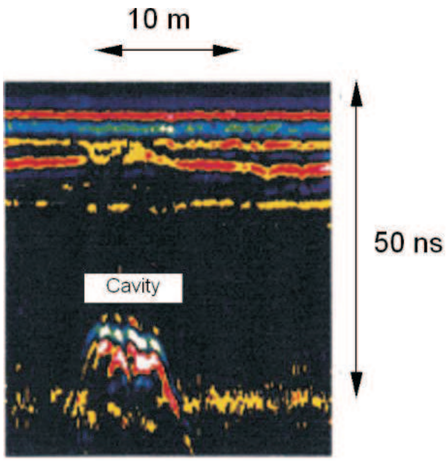
7. Interpretation

7.1. Collation of existing information and calibration of GPR data

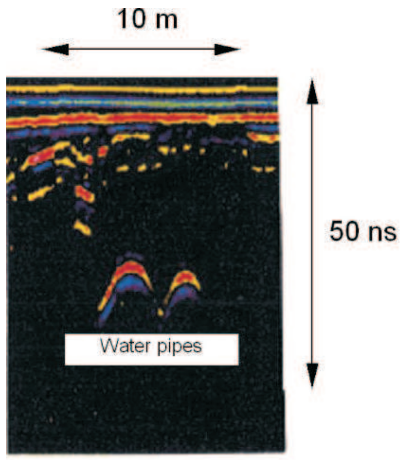
In order to interpret the survey results properly, it is important to collate the GPR data with the site information. Subsurface calibration of materials and depths are normally conducted by excavating test pits, or by drilling coreholes or boreholes, at selected locations chosen from the GPR data.

7.2. Interpretation of results

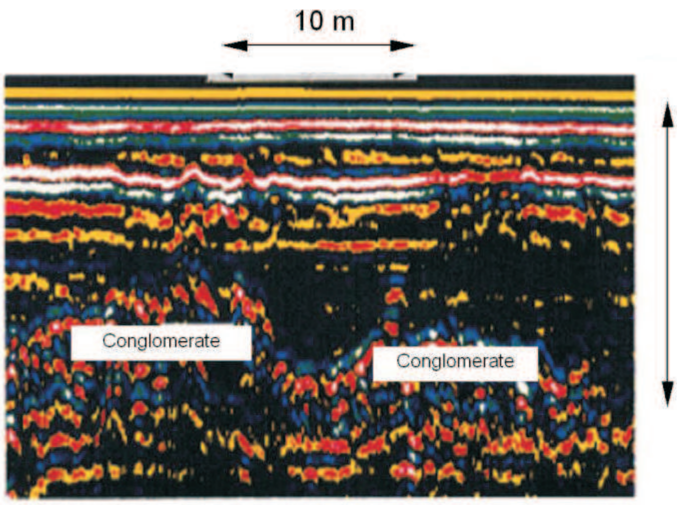
1. Reflection patterns in GPR data are interpreted as geological boundaries, buried utilities, cavities, etc, by recognizing their diagnostic patterns. Identification of multiple layers in road pavements, or of repetitive targets such as steel reinforcing bars in concrete, may be performed



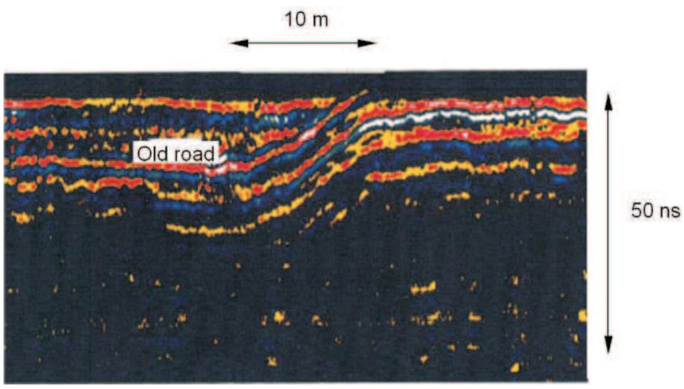
(a) Cavity detected at 0.9 m depth beneath a road. A cavity often generates a reflection pattern consisting of multiple hyperbolae. A grid of parallel GPR lines are required determine the lateral extent of such cavities.



(b) Two buried domestic tap water pipes separated by 4 m and lying at a depth of 0.5 m. The GPR profile was recorded in the direction perpendicular to the pipes. A buried pipe typically generates a hyperbolic reflection pattern projected downwards.



(c) Image reflected at a upper boundary of a conglomerate layer between 1 and 2 m deep beneath a road. Because the ratio of vertical depth to horizontal distance is large, minor ups and downs of the reflector appear exaggerated on this section.



(d) Image of an old asphalt road at a depth of approx. 0.4 m depth, covered with fill material lying against an inclined bank.

Fig. 6. GPR survey examples recorded on roads using 500 MHz antenna. (Data courtesy of SEGJ).

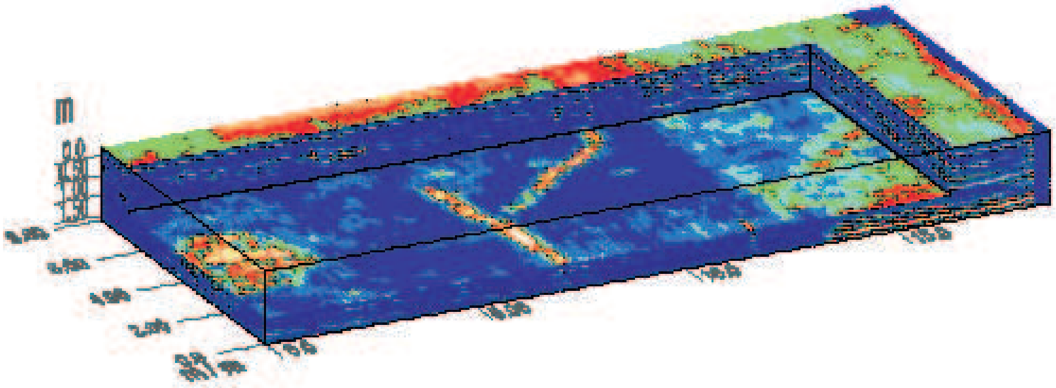


Fig. 7. 3-D GPR survey recorded at a urban construction site showing a Time Slice at 1.0 m depth. This image was compiled from 32 survey lines recorded on a grid at 0.25 m spacing, using a 400 MHz antenna. A circular archaeological ruin is visible on the left of the image. A buried pipe with angled T-junction lies in the centre. The green and red surface pattern on the right is due to tiles from a pavement, this overlies multiple compacted layers. (data courtesy of Georadar Research).

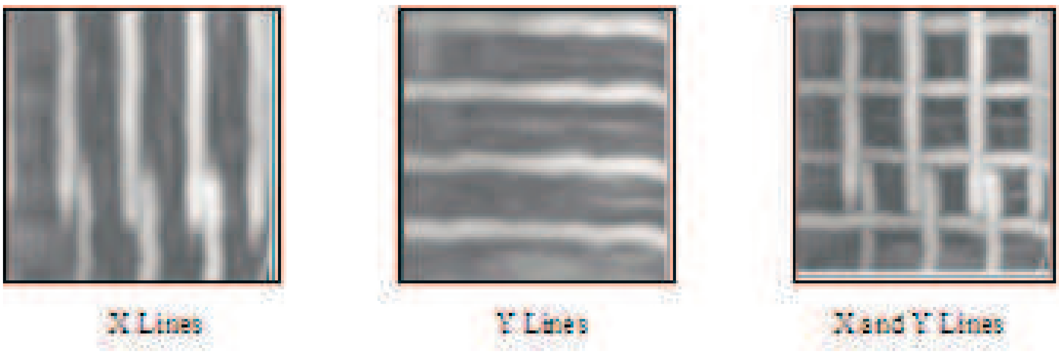


Fig. 8. Image of steel reinforcing bars in concrete floor of building. GPR survey lines were recorded in both X and Y directions at 10 cm spacing using a 1.5 GHz antenna. The data from the two grids was then superimposed on top of each other to give the combined image on the right. (data courtesy of R. Roberts, GSSI).

automatically using commercial programs and the results plotted graphically showing the depth and location of the targets.

2. The survey results are interpreted with due consideration for possible sources of error in measurement and analysis. Other complimentary geophysical investigation methods, such as electromagnetic, magnetometer or resistivity surveys, may be performed where appropriate and are often helpful to assist and complement the GPR data.

Targets are recognized and classified with reference to the objectives of the survey. Reflections on the GPR profiles are interpreted as geological boundaries, pipes, buried objects, voids and cavities. Examples of targets from GPR surveys performed on roads are shown in Figure 6.

In some cases it may be difficult to uniquely interpret the results of a GPR survey. In such cases careful observation of other features at the site, including the presence of electrical junction boxes, water stop valves and sewage manhole covers, etc, may assist the interpretation. Confirmation of results by carefully digging selective test pits may be required to positively identify key services, such as optic fibre cables, or high-voltage electrical cables.

3-D displays and Time Slices are used to show the relative locations of buried utilities or artefacts. Figure 7 shows the results of a 3-D survey recorded at an archaeological site.

For locating steel reinforcing bars in concrete, small grids typically 0.6x0.6 m are recorded with survey lines running in both X and Y directions with typically 5 cm spacing between the lines. This survey method is useful prior to drilling through concrete floors or walls in buildings, to avoid hitting the steel stressing ducts or electrical cables. An example is shown in Figure 8.

For classifying complex geotechnical parameters derived from GPR field measurements, a two-stage coding system called the GPR Classification Index [34] may be applied using numerical descriptors as follows:

1. GPR Class This first parameter addresses the

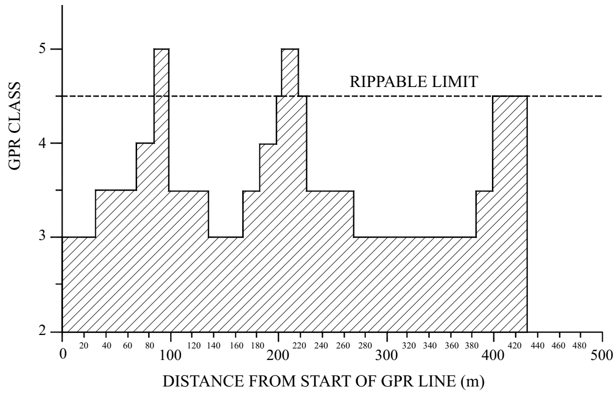


Fig. 9. Results of a GPR survey coded using the GPR Classification system (Yelf 2004b) and displayed in a simple graphical format, showing the interpreted rock condition along the route of the proposed excavation for a fibre-optic cable. The Class 5 sections represent very hard rock (>60 MPa) requiring explosives or hydraulic machine hammering, whereas the Class 3 zones indicate softer ground which can be ripped by a Caterpillar D8 bulldozer ploughing the cable directly into the ground. The dashed line is use to show the ripple limit for a Caterpillar D8 bulldozer. This type of information is readily interpretable and very useful to construction engineers to plan the appropriate types of plant equipment for long distance cable trenching projects.

essential engineering question that needs to be answered by the GPR survey; e.g. the perceived stability of a tunnel roof, or the relative excavatation difficulty of the ground for laying a pipeline or cable. The classification scale ranges from 0 to 5, in increments of 0.5, with Class 1 representing good or stable condition and Class 5 indicating extreme, bad or unstable condition. The scale range is established by on-site calibration against actual ground conditions. A zero value is used to indicate that no data is available for that section. The results are plotted graphically so that long sections (often covering many 10's of kilometres) can be readily interpreted by non-technical persons. An example is shown in Figure 9.

2. **Rock Type Descriptor** The second part of the classification system uses a two-digit number for describing the local soil or rock type and its weathering condition. For example the value 2.4 might be used, where first number (2) designates a Limestone rock type and the second value (4) designates that the rock at this locality has a hard cemented condition. This classification system is suitable for inclusion with GPS into GIS databases and also for coding of large GPR data sets with neural networks.

8. Outcomes of Survey and Reporting

1. The outcome of the GPR survey should normally include at least the following information:
   (a) Survey location map.
   (b) GPR profiles, either printed or in an electronic form which is viewable on computer screen, labelled with identified sub-surface features.
2. A GPR survey report should normally describe in the following:
   (a) Outline of the survey objectives.
   (b) Description of survey method used.
   (c) Type of GPR equipment used, including antenna frequencies and recording time range.
   (d) Data processing routines applied.
   (e) Survey results.
   (f) Interpretation.
   (g) Classification or coding of results (if required).
   (h) Conclusions and recommendations (if appropriate).

A site plan showing the location of the survey lines and the raw GPR profiles are normally the minimum outputs required. Map scales, the compass direction and relevant geographical site features should be marked on the plans and radargrams to assist interpretation.

Project reports should include a description of the field measurement method, GPR equipment type, antenna(e) frequency, instrument recording parameters, data processing and analysis techniques used. The GPR data should be clearly labelled and the results of the survey expressed so they are easy to understand.

For major GPR projects, the outputs may be classified into coded numerical engineering parameters (e.g. using the GPR Class system described in section 7.2) and plotted graphically, or incorporated into a GIS database.

Where nontechnical persons may use the outcomes of the report, it may appropriate to include a cautionary warning that GPR profiles show the intensity of electromagnetic waves reflected from objects both under the survey lines and also possibly from above the ground. Therefore some spurious features appearing on the radargrams may not always appear to be consistent with subsurface structures.

9. Future Developments

The penetration depth of GPR systems in use today is limited by the transmitted power. They use high voltages (up to 1,000 volt impulses) and low frequency (25–50 MHz antennae), which can reach up to 40 m depth in low conductivity ground conditions. Future GPR systems will deploy a new generation of UWB current-driven antenna, rather than voltage-driven antenna. These have the advantage of being able to transmit much higher mean power into the ground, and also use a smaller footprint, enabling them to be mounted inside robotic mining machines. Penetration depths of the order of 1,000 m are feasible using array based systems (Harmuth pers. com. 2006).

10. Conclusion

GPR is a powerful diagnostic tool for civil and geotechnical engineering. To obtain the best results it must be applied correctly by properly trained personnel, who are familiar both with the physical principles of the method and also of its limitations. The resultant data should be interpreted carefully, combining the relevant information of above ground and subsurface features. Calibration of the results using boreholes or test pits is recommended.

Acknowledgment

The original version of this document was prepared in cooperation with the Society of Exploration Geophysicists Japan and the Australian Society of Exploration Geophysicists. The author gratefully acknowledges the contribution of SEGJ and ASEG geophysicists and engineers to this paper, notably Prof. Yuzuru Ashida of Kyoto University, Toshiaki Takeuchi of OYO Corporation Japan, Hidetoshi Miura of Terra Corporation Japan and Koya Suto of Terra Australis Geophysica.

Manuscript received November 15, 2006

References

[1] Allred B., Daniels J. and Vendl M. Basics of GPR // Workshop notes presented at 11–th International GPR Conference (Ohio State Univ., Ohio, USA). – 2006 – 41 P. (on CD-ROM)

[2] Annan A.P. Radar CDP and WARR Soundings: Principles and Interpretation // A-Cubed Technical Note 15. – 1985. (Sensors & Software, Canada).

[3] Bakker M. The internal structure of Pleistocene push moraines – PhD Thesis, Queen Mary College, Univ. of London: Published by TNO Netherlands. – 2004. – 177 P.

[4] Benson A.K. Applications of ground penetrating radar in assessing some geological hazards // Journal of Applied Geophysics – 1995. – V. 33. – P. 177–193.

[5] Daniels D.J. Ground Penetrating Radar. 2-nd Edition. – London: The Institute of Electrical Engineers. United Kingdom. – 2004.

[6] Davies J.L. and Annan A.P. Ground -penetrating radar for high-resolution mapping of soil and rock stratigraphy // Geophysical Prospecting – 1989. – V. 37. – P. 531–551.

[7] Doolittle J.A. Minzenmayer F.E., Waltman S.W. and Benham E.C. Ground penetrating radar soil suitability map of the conterminous United States // Proc. of the 9-th International GPR Conference SPIE Vol 4758 (Santa Barbara, CA, U.S.A.) – 2002. – P. 7–12. (on CD-ROM)

[8] Doolittle J.A., Collins M. and Mount H. Assessing the appropriateness of GPR with soil geographic data base // Proc. of the 7-th International GPR Conference (Univ. of Kansas, Lawrence, USA). – 1998. – P. 393–397. (on CD-ROM)

[9] Davis J.L., Rossiter J.R., Mesher D. and Dawley C.B. Quantitative Measurements of Pavement Structures Using GPR // Proc. of the 5-th International GPR Conference, V. 1 (Kitchener, Ontario, Canada). – 1994 – P. 319–334.

[10] Goodman D. GPR Time Slices of the Villa of Emperor Trajanus, Arcinazzo, Italy (AD 52—117) // Proc. of the 9-th International GPR Conference (Santa Barbara, CA, U.S.A.) – 2002. – P. 268–272. (on CD-ROM)

[11] Green A., Holliger K., Horstmeyer H., Maurer H., Tronicke J., and Van de Kruk J. Three-dimensional Acquisition, Processing and Imaging of GPR Data // Applied Environmental Geophysics Group, ETH Zurich, Switzerland, presented at Advanced GPR Workshop, Proc. of the 9-th International GPR Conference (Santa Barbara, CA, USA). – 2002 (on CD-ROM)

[12] Francke J. and Yelf R. Applications of GPR for Surface Mining // Proc. of the 2nd International Workshop on Advanced GPR . A Yarovoy (ed). Published by IEEE. (International Research Centre for Telecommunications and Radar, Delft University, Netherlands). – 2003. – P. 115–119.

[13] Harmuth, H.F. Radiation of Nonsinusoidal Electromagnetic Wave Advances in Electronics

& Electron Physics // Suppplement. Academic Press Inc., USA. – 1990. – V. 23.

[14] Harmuth H.F., Boules R. and Hussain M. Electromagnetic Signals : Reflection, Focusing, Distortion, and Their Practical Applications. – New York: Kluwer Academic/Plenum Publishers, USA. – 1999.

[15] Hugenschmidt H. Railway track inspection with GPR: some examples from Switzerland // Proc. of the 7–th International GPR Conference (Univ. of Kansas, Lawrence, USA) – 1998. – P. 197—202.

[16] Jol H.M. and Bristow C.S. GPR in sediments: advice on data collection, basic processing and interpretation, a good practice guide. In: Bristow, C.S. and Jol, H.M. (eds.), GPR in Sediments, Geological Society of London, Special Publication 211. – 2003. – P. 9–27.

[17] Kong F. Choice of antenna type and frequency range for testing concrete structures // Proc. of the 8-th International GPR Conference (Gold Coast, Australia). – 2000. – P. 268–272.

[18] Liu L. and Zhu L. GPR Signal Analysis: can we get deep penetration and high resolution simultaneously? // Proc. of the 10-th International GPR Conference V. 1 (Delft, Netherlands). – 2004. – P. 263–266.

[19] Maierhofer C. and Kind T. Application of impulse radar for non-destructive investigations of concrete structures // Proc. of the 9-th International GPR Conference SPIE Vol 4758 (Santa Barbara, CA, U.S.A.) – 2002. – P. 382–387.

[20] McCann D.M. and Forde M.C.Review of NDT Methods in the Assessment of Concrete and Masonry Structures // NDT & E International – 2001. – V. 34, Issue 2. – P. 71–84.

[21] Noon D., Longstaff L. and Yelf. R.J. Advances in the development of Step Frequency GPR // Proc. of the 5-th International GPR Conference V. 1 (Kitchener, Ontario, Canada). – 1994. – P. 117–131.

[22] Roberts R. Enhanced Target Imaging in 3D Using GPR Data from Orthogonal Profile Lines // Proc. of the 9-th International GPR Conference SPIE (Santa Barbara, CA, U.S.A.). – 2002. – V. 4758. – P. 256–260.

[23] Saarenketo T. Electrical properties of water in clay and silty soils // Journal of Applied Geophysics – 1998. – V. 40. – P. 73–88.

[24] Shihab S. and Al-Nuaimy W. Hyperbola Fitter for Characterisation of Cylindrical Targets in GPR Data // Proc. of the 11-th International GPR Conference (Ohio State Univ., Ohio, USA). – 2006. (on CD-ROM)

[25] Smith D.G. and Jol H.M. Ground-penetrating radar: antenna frequencies and maximum probable depths of penetration in Quaternary sediments // Journal of Applied Geophysics – 1995. – V. 33. – P. 93-1.

[26] Society of Exploration Geophysicists of Japan Advisory Committee on Standardization // Application of Geophysical Methods to Engineering and Environmental Problems – 2004. – 301 P.

[27] The Concrete Society. Guidance on Radar Testing of Concrete Structures, Slough, UK: Concrete Soc. Technical Report. – 1997. – 114 P.

[28] Turner G. The Influence of Subsurface Properties on GPR Pulses // PhD Thesis. Macquarie Univ, Sydney Australia. – 1993. – 174 P.

[29] Utsi E. Improving Definition — GPR Investigations At Westminster Abbey // Proc. of the 11th International GPR Conference (Ohio State Univ., Ohio, USA). – 2006. (on CD-ROM)

[30] Ulriksen C.P. Application of impulse radar to civil engineering // PhD Thesis Lund University of Technology, Sweden. Published by Geophysical Survey Systems Inc, Salem, NH, USA. – 1982 – 178 P.

[31] Wensik W., Greeuw G., Hofman J. and Van Deen J. Measured underwater near field E-patterns of a pulsed, horizontal dipole antenna in air: comparison with theory of continuous wave, infinitesimal electric dipole // Geophysical Prospecting – 1990. – V. 38. – P. 805–830.

[32] Wollny G. and Berktold A. GPR measurements on active, stabilised and potential landslides // Proc. of the 7th International GPR Conference on CD-ROM (Univ. of Kansas, Lawrence, USA). – 1998. – P. 401–406.

[33] Yelf R.J. Where is True Time Zero? // Proc. of the 10-th International GPR Conference Vol. 1 (Delft University, Netherlands). – 2004a. – P. 279–282. (on CD-ROM)

[34] Yelf R.J. and Al-Nuaimy W. Classification System for GPR Parameters // Proc. of the 10-th International GPR Conference V. 1 (Delft University, Netherlands). – 2004b. – P. 407–410. (on CD-ROM)