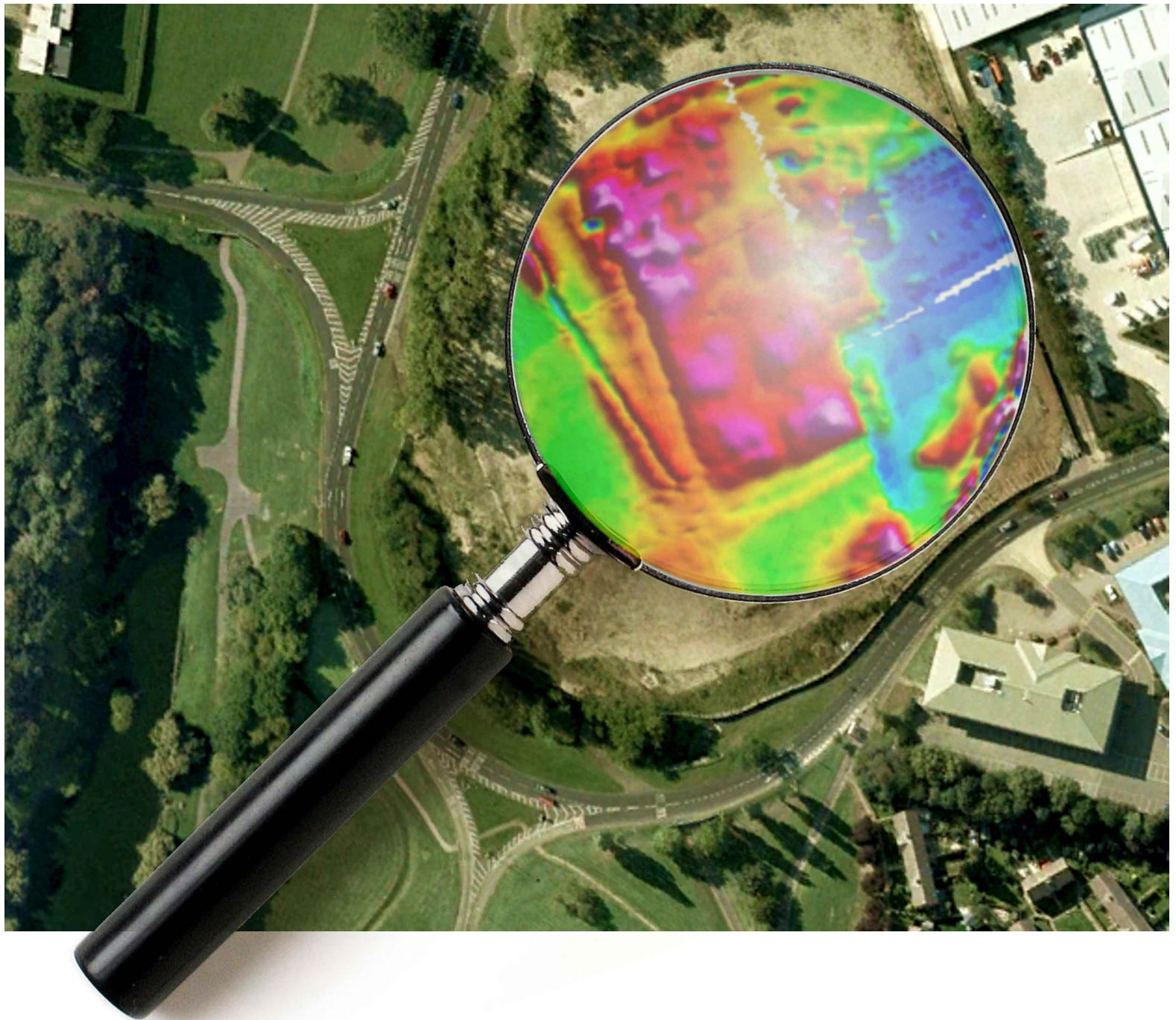


A REFERENCE FOR GEOPHYSICAL TECHNIQUES AND APPLICATIONS



RSK

Edition 4.0

ABOUT THIS BOOK



The intention of this book is to provide a useful reference text for land based near-surface geophysical techniques. It provides some basic theoretical background for the most commonly used (and useful) techniques, and their application is illustrated through a series of case studies which are grouped into familiar themes.

The many examples used throughout the text demonstrate that in the right circumstances, when done by people with the right qualifications and expertise, geophysical tools can deliver valuable information to an integrated site investigation.

It is not appropriate to use geophysics in every case. It is very rarely appropriate to use geophysics in isolation.

The first task is to get good advice.

Hopefully this book will be a helpful starting point.



A handwritten signature in purple ink, reading 'G Tuckwell'.

Prof George Tuckwell *Ph.D. CGeol CSci*
Divisional Director, RSK



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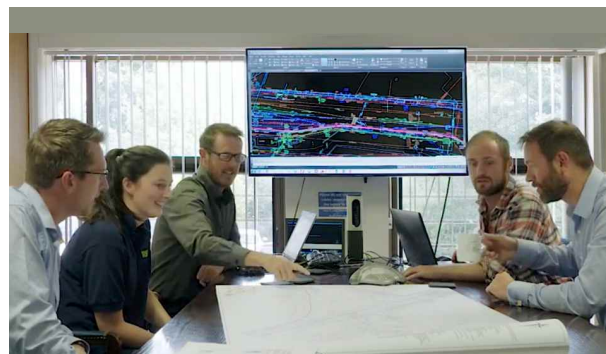
HOW TO USE GEOPHYSICS



Planning an integrated site investigation

Geophysical surveying is just one set of tools available to investigate the ground or built environment.

Regardless of the scale to a site investigation, it invariably adheres to British Standard BS 5930:2015 'Code of practice for site investigations'. Normally, the acquisition and interpretation of geophysical data will be planned as part of an integrated ground investigation with intrusive investigations designed to calibrate the interpretations of the geophysical data, or target anomalies to determine their cause. It is best practice to consider the applicability of geophysical methods to the various aspects of the site investigation programme, for example, to assist in the siting of boreholes, trial pits, etc. at the earliest stages of planning.



The choice of the correct geophysical method, or combination of methods is absolutely essential, both from the point of view of maximizing the success of the survey and obtaining the desired geological information on a cost-effective basis. Geophysics done badly, or using the wrong technique(s) will be a waste of money.

Using the right people

The implementation and interpretation of a geophysical survey requires expert personnel and should be entrusted to an organisation specialising in this work. The organisation should provide the client with a geophysical advisor who, in addition to determining the suitability of the various geophysical techniques available, can design and oversee the geophysical survey, acting as point of contact for his client. BS5930 requires that this expert should be qualified as a chartered geologist or chartered scientist on the basis of their expertise in near-surface geophysics.



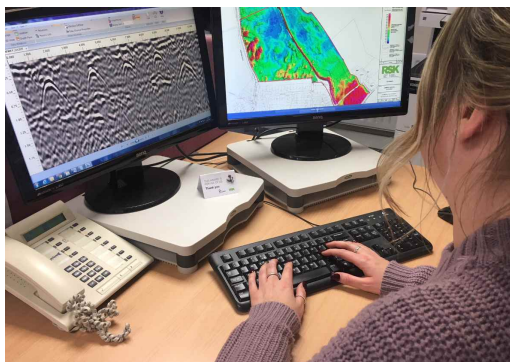
The
Geological
Society

*Professional geophysicists are
chartered through the Geological
Society*

The principal role of the geophysical advisor is to understand the requirements of the client in terms of the information required from the overall site investigation and the purpose for which the information is required. This understanding will form the basis of their advice regarding the possible use of geophysical techniques to reliably provide the required information to an accuracy suitable for the intended purpose. They should set out the benefits of the survey, its limitations, and its risks with specific reference to the information that the survey will deliver.

When the decision is made to undertake a geophysical survey, it is essential to ensure that the data acquisition, processing and interpretation are done by suitably qualified geophysicists, with experience of interpreting data relating to the targets of the survey (for example, archaeology, buried services, UXO, glacial geology, etc.). Personnel not expert in the equipment, and the science behind the equipment, will not react correctly to unexpected ground conditions on site, nor to changes in scope or access; they will not be able to adequately QC data during acquisition, and they will not provide continuity of expertise. Personnel unfamiliar with a particular target type risk misinterpreting the geophysical data and delivering misleading or incomplete information to the client.

Data processing and reporting



Data should be quality checked on site as part of the data collection methodology, and also checked at the end of each site visit by the lead geophysicist. Often initial indications from the raw un-processed data can inform the ongoing data collection phase of the project. In some cases data can be transmitted back to the office to provide the client with early interpretations.

The collection of good field data is only half of the picture. Careful processing of the data must be undertaken by an experienced geophysicist in order to produce accurate interpretations, and in order to avoid the misinterpretation of spurious signals in the data. It can take several days to process the data collected during one day in the field.

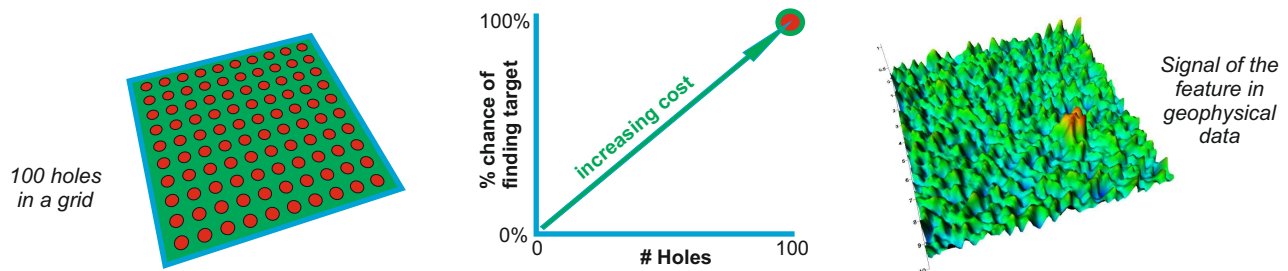
In every case the objective is to integrate the geophysical data intelligently with all other relevant site information, and produce an accurate interpretation that provides information that the client needs. Final interpretative drawings and reports should be signed off by a suitably experienced chartered professional.

WHEN TO USE GEOPHYSICS



The statistics of finding things

Say you need to determine whether a particular feature is present, perhaps it is a UST, or a solution feature, it doesn't matter what for now. Say that feature has dimensions 1/10th that of the search area, so you are looking for a 1m by 1m thing in a 10m by 10m area, or a 10m by 10m thing in a 1 Hectare area.



To be 50% sure of finding it by digging you would need 50 holes. To put this another way, after 50 holes, if you haven't found it then maybe it isn't there, or maybe there is a 50% chance you just didn't find it. To be 100% sure of finding it, or proving its absence, you would need 100 holes. If the feature is detectable by geophysics, you would need just one hole.

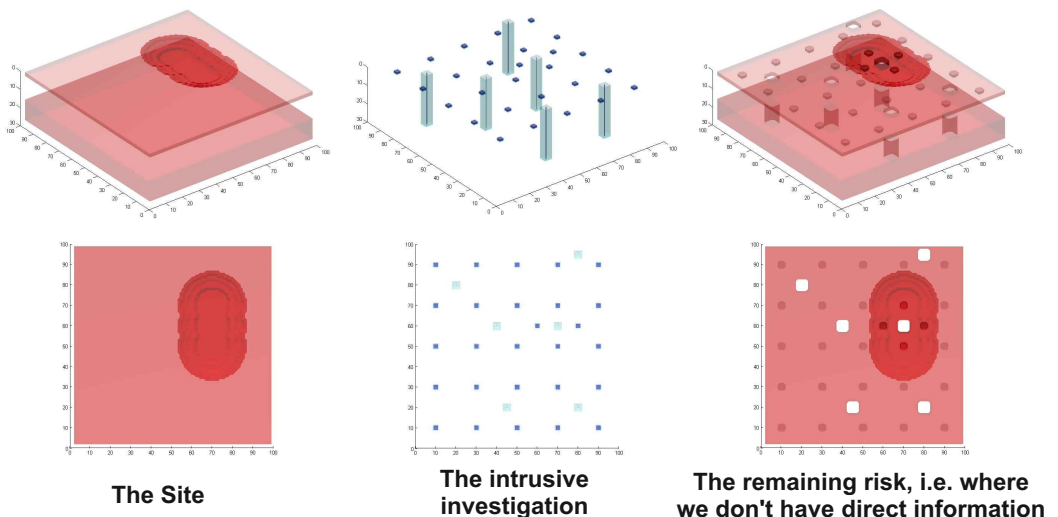
Risk and information

Below are schematic views of a site which illustrate the balance of risk and information inherent in all site investigations. Red represents risk of unknown conditions, which equates to the need for information. Blue represents the information provided by a series of trial pits and boreholes.

Boreholes and trial pits provide direct information on a fraction of the volume of ground.

The balance of risk therefore hangs on the likelihood that some variation, problem or obstruction exists in the big red spaces remaining. This depends on the site, its history, and its geology. Assessing this remaining risk relies on the expertise of the SI specialist. What is done relies on the informed risk decisions made by the client.

What if a geophysical survey could turn it all blue?



Advantages of using geophysics

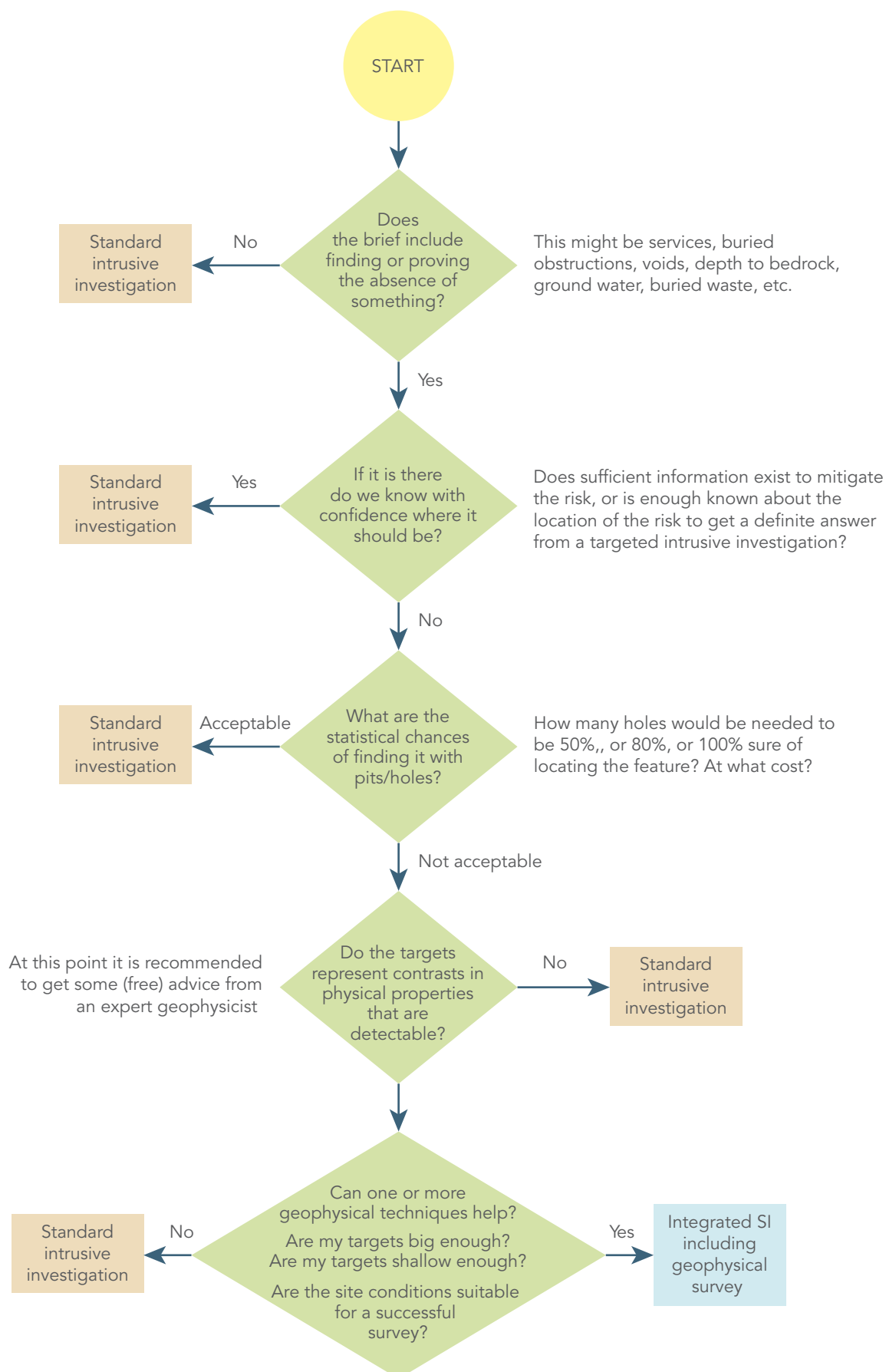
CONTINUOUS DATA	Able to fill in the gaps between intrusives that tell you everything about a point, by telling you something about everything in between, leading to lower risk and a more accurate and detailed ground model
NON-INTRUSIVE	Safer in hazardous environments – as your not exposing personnel to contaminated material or creating new flow paths.
NON-DESTRUCTIVE	Investigate structures and ground without effecting their integrity or stability.
RAPID	Large areas can be covered quickly in relatively short periods of time.
COST EFFECTIVE	Provide a 'quick look' at a large area. Features identified can be targeted rather than approaching a site 'blind'.
SAFER	Improve safety of construction works by mapping buried hazards.

WHEN NOT TO USE GEOPHYSICS



Decision Flowchart

The first step is to gather all of the available information about the site and to document the remaining unknowns. In designing the site investigation to address those unknowns, the following simple decisions are before you:



GEOPHYSICAL TECHNIQUES & EQUIPMENT

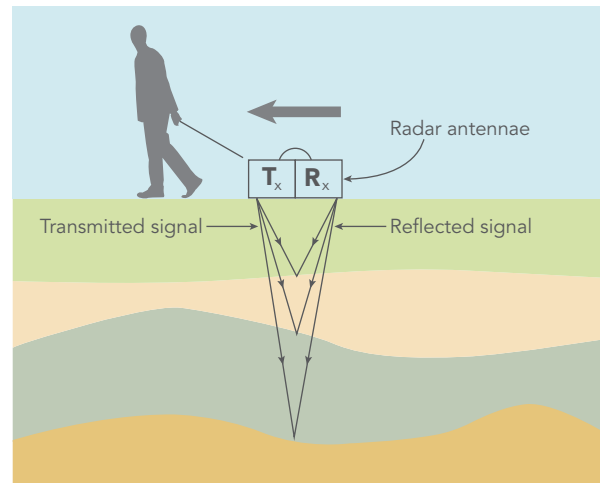


GROUND PENETRATING RADAR



Applications

- ✓ Locating below ground services
- ✓ Construction details (e.g., location of buried foundations and basements, slab thickness, reinforcement detail, void detection, locating beams, bridge deck surveys)
- ✓ Depth to bedrock and water table
- ✓ Locating fractures, sinkholes or cave systems
- ✓ Locating contamination plumes and channel features
- ✓ Locating underground storage tanks and buried drums
- ✓ Archaeology (e.g., location of graves and artifacts)
- ✓ Locating animal burrows
- ✓ Railway ballast and highway pavement analysis
- ✓ Novel uses such as tree root and water leakage location



Basic Theory

In Ground Penetrating Radar (GPR) surveys, electromagnetic waves at radar frequencies are transmitted into the ground or a structure. This energy is reflected back to the surface when it encounters significant contrasts in dielectric properties.

A radio wave transmitter (T_x) located at the surface is used to generate a short pulse of radar waves which penetrate into the subsurface. Some of the energy carried by these waves is transmitted to greater and greater depths, while some of the energy is reflected back towards the surface receiver (R_x) whenever a contrast in dielectric properties is encountered (see **above right**). The amount of energy reflected is dependent on the contrast in electrical properties encountered by the radio waves.

The receiver measures the variation in the strength of the reflected signals with time. The resulting profile is called a 'scan' and is a one-dimensional representation of the subsurface beneath the antenna. To build up a two dimensional section of the subsurface (a radargram), the antenna is traversed across the surface to collect a number of adjacent scans. Conversions to depth sections may be made providing there is sufficient information regarding the dielectric properties of the material(s) surveyed.

Data can be processed and presented as individual radargrams. These are essentially two-dimensional cross sections of the sub surface. Modern software now enables stacking of adjacent radargrams and the construction of three-dimensional data cubes. Horizontal slices (or "time slices") through the data at the desired depth enables visualisation of the reflection strength across the survey area. This is an invaluable approach in the detection and tracing of linear targets (e.g pipes and walls) and complex three dimensional buried structures.

The type of GPR equipment is selected depending on the target object and site conditions as shown below:

Frequency	Typical depth of penetration (bgl)	Common applications
2600 MHz	to 0.4m (12in)	Concrete evaluation
1500 MHz	to 0.7m (20in)	Concrete evaluation; void detection
900 MHz	0–1m (0–3ft)	Concrete evaluation; void detection
400 MHz	0–3m (0–9ft)	Utility, engineering & environmental, void detection
200 MHz	0–6m (0–20ft)	Utility, geological, engineering and environmental
100 MHz	0–12m (0–40ft)	Geological, engineering
50 MHz	0–25m (0–75ft)	Geological



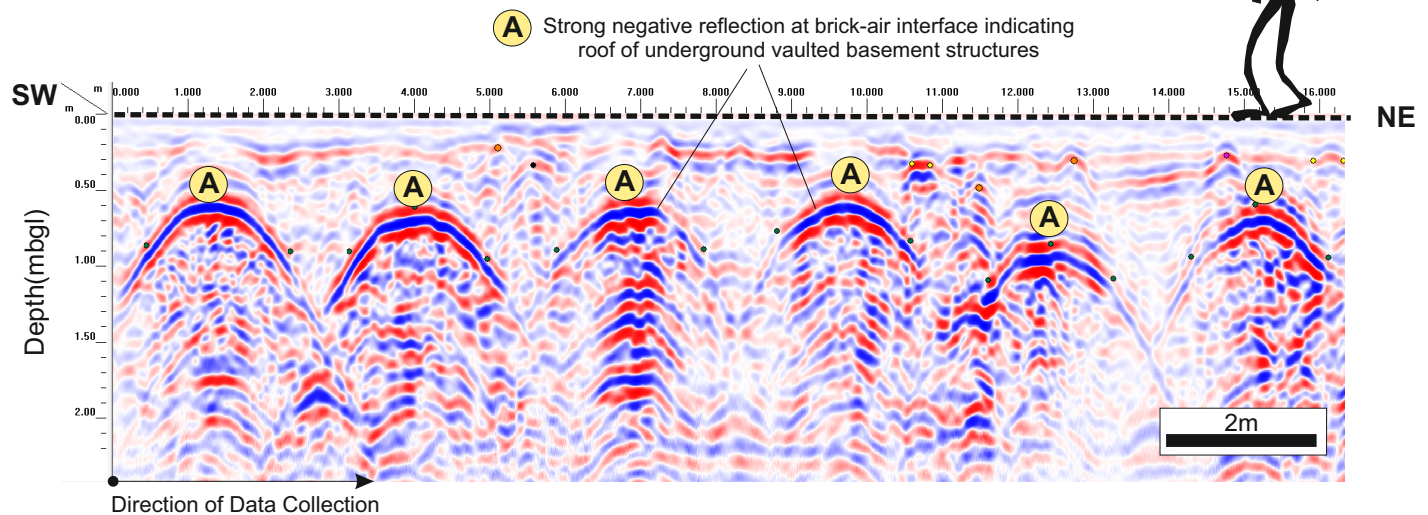
GPR instruments can operate at a range of different frequencies to investigate a range of targets and depths (see **centre image**). The versatility of GPR means that the radar antenna can be handheld, pulled across the ground or pushed on a kart (see image **left**). The latest state-of-the-art GPR equipment also includes multiple channel technology which helps to minimise the data acquisition time on site (see image **right**, deploying a dual polarised 34 channel system on a road at full traffic speed).

GROUND PENETRATING RADAR



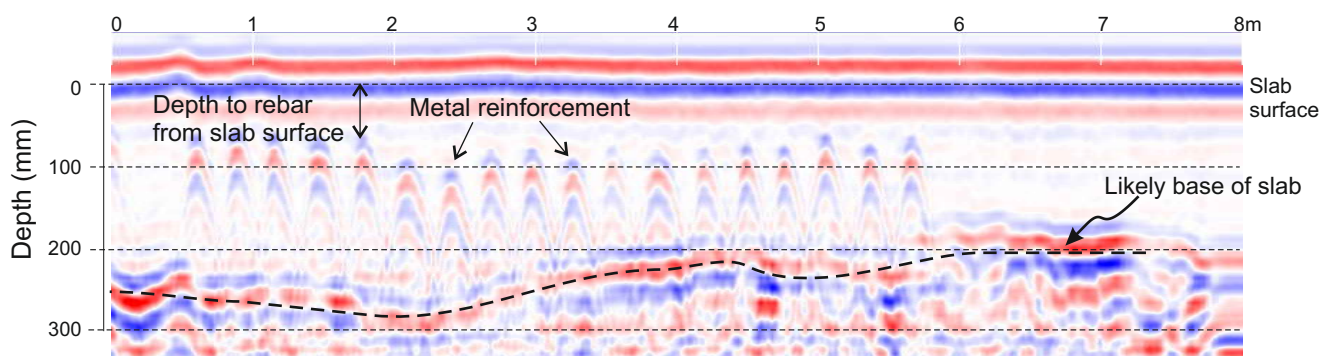
GPR Data Examples - Structures and Basements

1 An example of mid frequency radar data collected on a pavement over basements

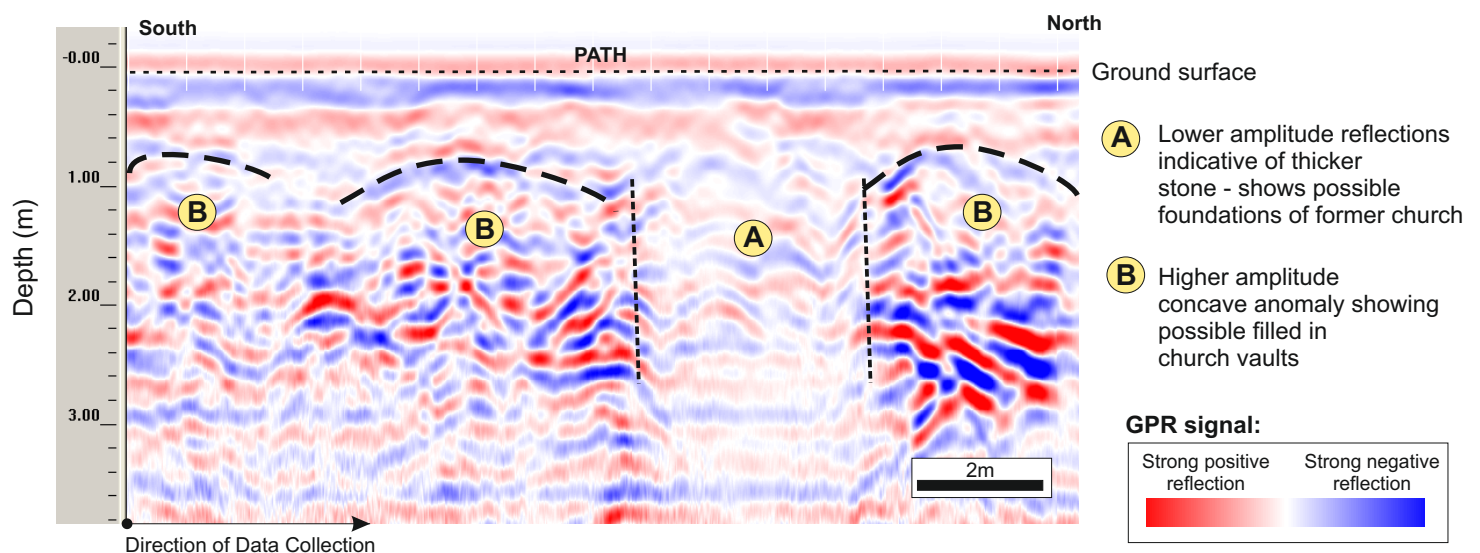


2 An example of high frequency (1.5GHz) radar data collected over a concrete slab

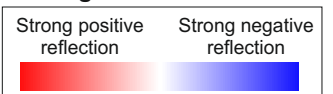
Individual rebar are identifiable from their triple hyperbolic diffractions. The maximum depth of investigation here is approximately 300mm.



3 An example of mid frequency (400MHz) radar data collected over a former churchyard



GPR signal:



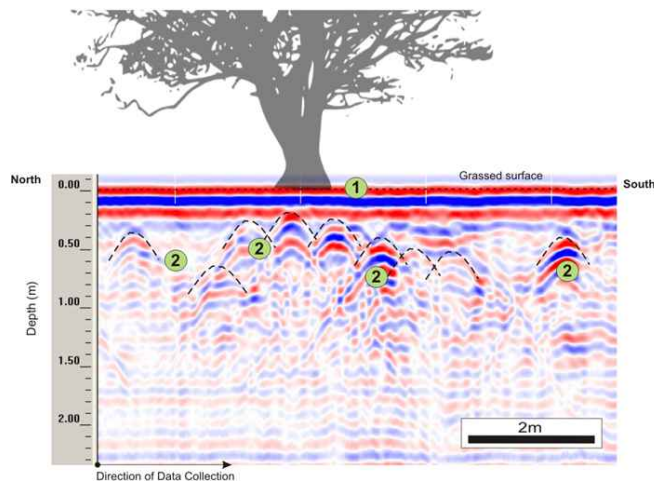
A stronger reflection is indicative of a higher contrast in material properties

GROUND PENETRATING RADAR

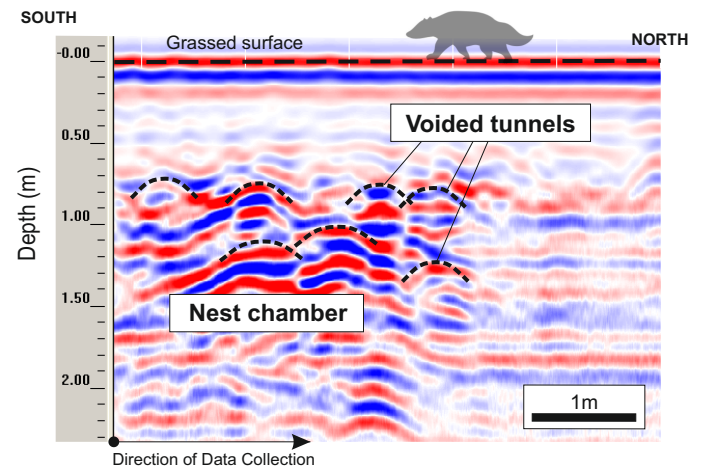


GPR Data Examples - Buried Utilities, Voids and Novel Uses

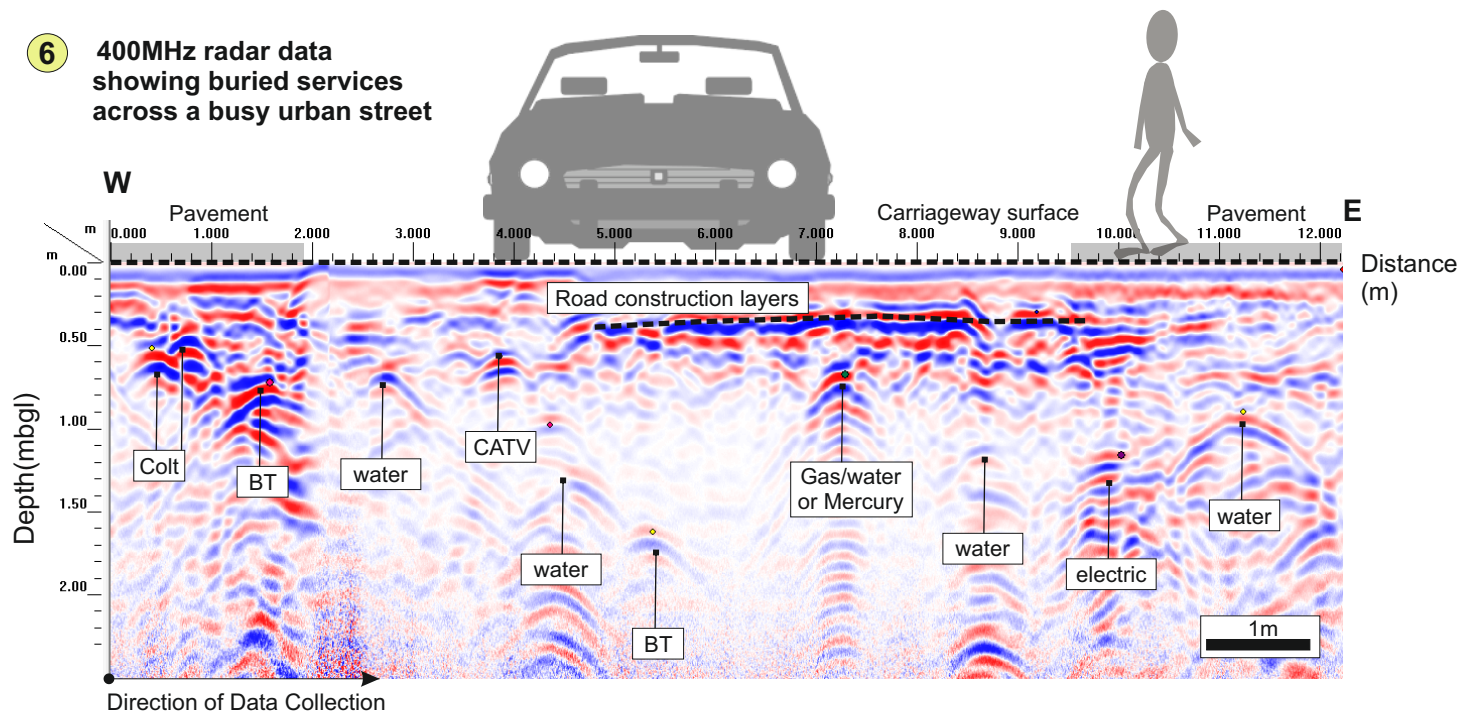
4 400MHz radar data showing multiple tree roots



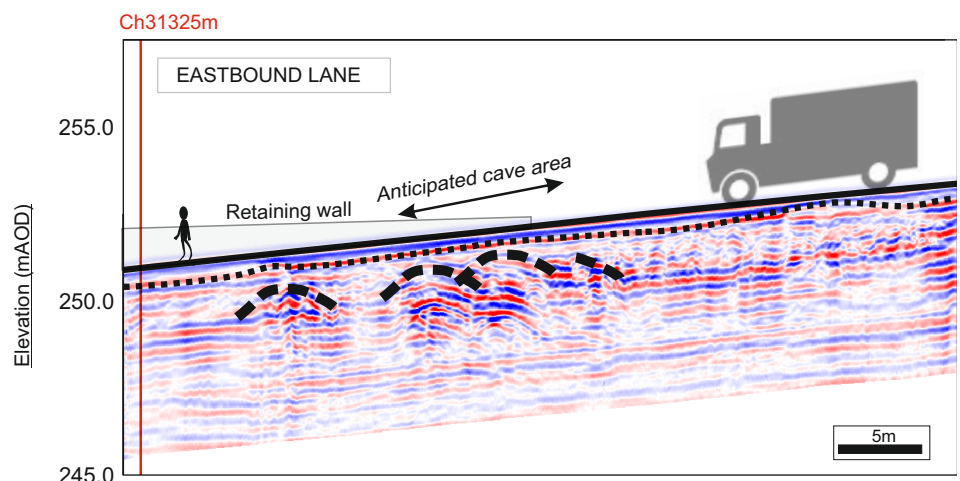
5 400MHz radar data collected over a badger sett



6 400MHz radar data showing buried services across a busy urban street



7 Low frequency (200MHz) radar data collected along a road to detect possible voided ground or faulted ground associated with caves in the limestone bedrock



Applications

- ✓ Locating dissolution features
- ✓ Locating sub-surface voids and mineshafts
- ✓ Mapping variation in near surface geological strata
- ✓ Mapping buried utilities
- ✓ Locating underground storage tanks (USTs)
- ✓ Locating Unexploded Ordnance (UXO)
- ✓ Mapping buried foundations

- ✓ Locating the boundaries of landfills
- ✓ Mapping leachate migration and contamination plumes
- ✓ Determination of layer thickness and conductivities
- ✓ Mapping and monitoring groundwater pollution
- ✓ Mapping saline intrusions
- ✓ Assessment of ground remediation

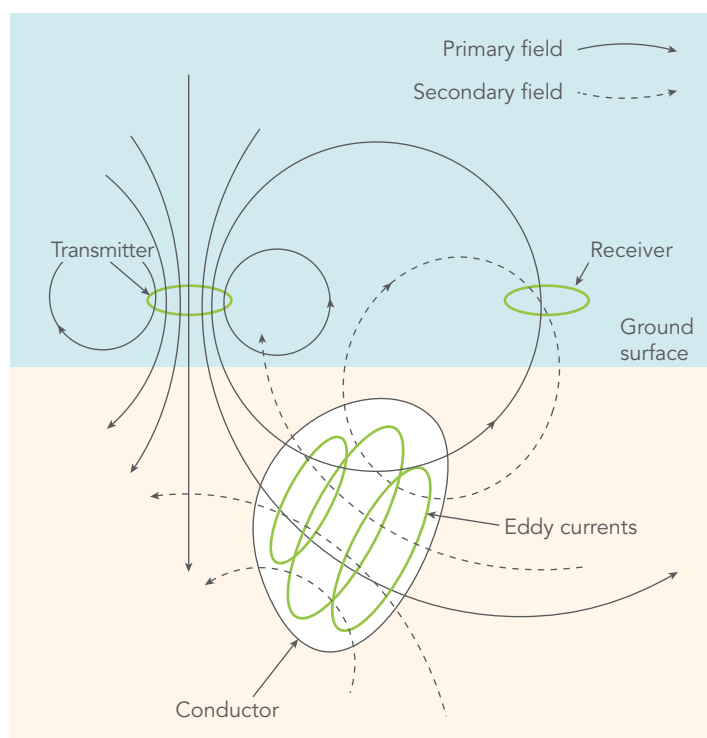
Basic Theory

There are two types of electromagnetic (EM) survey: the first one, based on frequency domain, measures the amplitude and phase of an EM induced field (**FDEM**), the second one, based on the time domain, measures the decay time of an electromagnetic pulse induced by a transmitter (**TDEM**).

EM Frequency Domain Ground Conductivity surveys

In **Frequency Domain Electromagnetic** surveying, the electrical conductivity of the ground is measured as a function of depth and/or horizontal distance. Different rocks (and buried objects / structures) exhibit different values of electrical conductivity. Mapping variations in electrical conductivity can identify anomalous areas worthy of further geophysical or intrusive investigation.

An alternating current, of variable frequency, is passed through a coil of wire (a transmitter coil). This process generates an alternating primary magnetic field which, in turn, induces very small eddy currents in the earth, the magnitude of which is directly proportional to the ground conductivity in the vicinity of the coil. These eddy currents then generate a secondary magnetic field, a part of which is intercepted by a receiver coil. The interaction between the primary and secondary magnetic flux and the receiver coil generates a voltage that is related to the electrical conductivity of the subsurface, expressed as milliSiemen/metre (mS/m).



The electromagnetic method is based on the induction of electric currents in the ground by the magnetic component of electromagnetic waves generated at the surface.

Rapid data collection

The collection of data over larger sites can be undertaken with mobile platforms, for example the Geophysical Equipment Exploration Platform (GEEP), developed at the University of Leicester in partnership with Geomatrix Ltd (as shown **below**). Mobile instrument platforms provide a means of quickly and efficiently collecting densely sampled high quality data from EM and magnetic instruments simultaneously.



*The CMD Explorer instrument shown **above** uses transmitter and receiver coils at either end of the boom. This version is a multi-depth sensor as the booms contain three pairs of coils at an increasing spacing.*



FDEM Data Examples

Delineating Landfill Boundaries

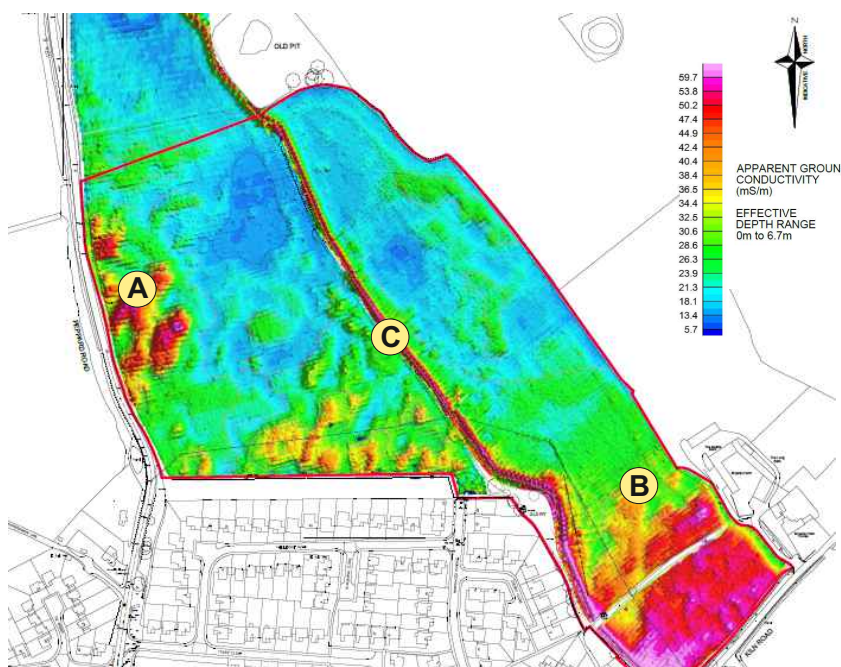
An EM survey can provide rapid reconnaissance information regarding the presence and location of buried services, foundations, storage tanks, obstructions, UXO, waste and contamination.

In this example (right) ground conductivity data were collected with a CMD Explorer over a closed landfill site to delineate the lateral extent of the waste, and to detect internal variations in waste type. Landfill boundaries can be interpreted as the boundary between the areas of low and high conductivity values (coloured blue and red respectively to indicate areas of undisturbed ground and areas of buried waste).

EM data can be integrated with other complimentary geophysical methods such as ERT in order to provide a comprehensive model of the site.



FDEM data is conventionally collected on foot along parallel lines across the target area. EM data is acquired with dGPS to accurately locate the data. This survey methodology enables rapid coverage of the site area (typically up to 2Ha per day).



Solution feature mapping

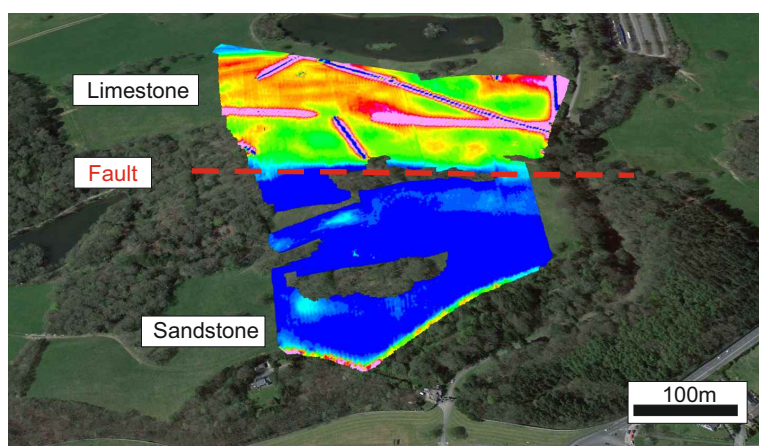
In this example (left) FDEM data were collected across a number of greenfield areas subject to historic chalk mining and potential solution features. A number of discrete anomalies (marked A) were detected. These were targeted in a subsequent borehole investigation and were found to contain thicker clay filled deposits over the chalk bedrock. Areas of higher conductivity (marked B and coloured pink) show where thicker superficial clays were present at the surface. The edge of such features can form 'feather-edge' areas where dissolution activity may be more likely.

The survey also detected a linear feature running NW-SE through the centre of the site (marked C). This corresponded to a metal gas main. This information was also of use in order to inform the safe locating of the follow up intrusive investigation.

Fault and bedrock mapping

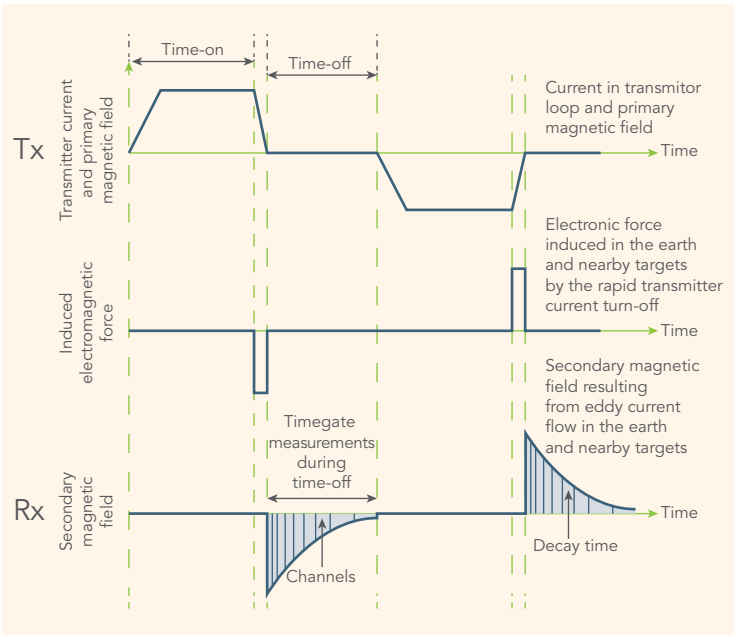
For this site (right), a FDEM survey was undertaken to delineate a fault indicated by British Geological Survey maps. The EM data clearly shows two different units of bedrock based on the conductivity values (warmer colours represent higher conductivity). To the north of the inferred fault (red line) lies higher conductivity limestone (shaded green) with lower conductivity sandstone to the south (shaded blue). At the interface lies a distinct boundary change which shows the presence of a near vertical fault offsetting the two lithological units.

A number of linear features were also present in the north of the area which correspond to buried services.



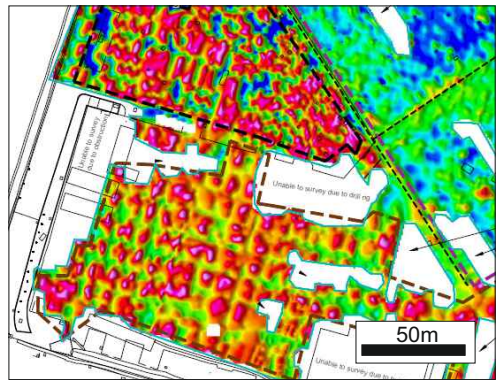
EM Time Domain surveys

In **Time Domain Electromagnetic (TDEM)** surveying, the instrument contains a powerful transmitter that generates a pulsed primary magnetic field, which induces eddy currents in nearby metallic objects (see **right**). A number of receiver coils mounted on the coil assembly measure the decay of these currents by recording the eddy currents at a number of distinct time intervals (time gates). By measuring voltages at specific times, information on the size of depth of buried objects can be better determined. This is because the decay of the eddy current is related to the properties of the target.



*Shallow TDEM data is conventionally collected on foot with the coils mounted on a wheeled kart based assembly. A Geonics EM61 instrument with GPS is shown **left**. The EM61 instrument acts as a very sensitive metal detector suitable for applications in the detection of both ferrous and non-ferrous metal.*

TDEM Data Examples



Locating buried structures at a Brownfield Site

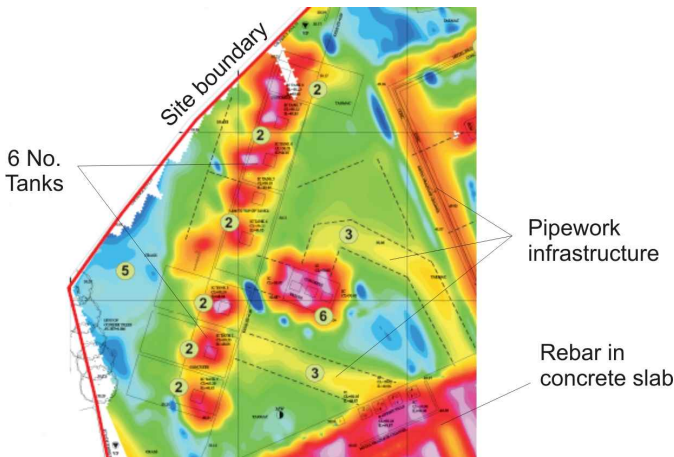
Brownfield sites are attractive targets for re-development but can be full of potential pitfalls and risks to the developer. Geophysics can help to significantly reduce those risks.

Shown to the **left**, the time domain EM-61 data provides plots of the variation in the induced potential (measured in mV) highlighting potential targets across the survey area. The data clearly shows the location of buried obstructions such as the foundations of former buildings and presence of piles, for this former manufacturing works in East London. The information from the geophysical survey was used to inform the subsequent intrusive survey which was able to target trial pits more precisely across the site, prior to the development of the site into a residential housing estate.

Detecting Buried Tanks and pipework infrastructure

Mapping variations in the electrical conductivity of the subsurface across a site can highlight anomalously conductive targets such as metallic tanks, pipework, ground contamination, buried waste, solution features and old foundations.

In the example shown **right** at a disused petrol filling station, buried tanks generate a strong response along with the associated pipework infrastructure. This data can help aid subsequent intrusive investigation so that the boreholes can be located close to, but at a safe distance from, the USTs.



Deep Transient Electromagnetics (TEM)

Typical TEM systems can provide rapid measurements from a few meters down (see previous page) to several hundred meters, depending on the size of the transmitter loop being used, available power from the transmitter and ambient electro-magnetic noise.

Deeper or later time TEM is a well-established technique for obtaining subsurface resistivity-conductivity data for mineral exploration and is increasingly being applied to hydrogeological mapping applications and to environmental and engineering site investigation studies. There is a strong correlation between the conductivity and properties of soils and bedrock, as such TEM is an effective way to map variations within rock and soil, for example mapping clay layers, conductive leachate in groundwater and seepage in earth embankments.

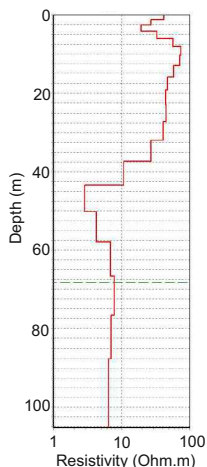
TEM systems for deeper investigation typically comprise a single or dual channel receiver with multiple, interchangeable transmitters and receiver coils. This provides the flexibility required to accommodate a broad range of applications and depths. The transmitter loop generally comprises an ungrounded loop of wire laid on the ground surface. The EM wave from the transmitter propagates into the sub-surface where eddy currents are generated in differing materials. These secondary EM fields are picked up at the surface by the receiver coils at multiple time intervals (see **right**). The rate of diffusion indicates the resistivity of the subsurface materials.

Data collection and presentation

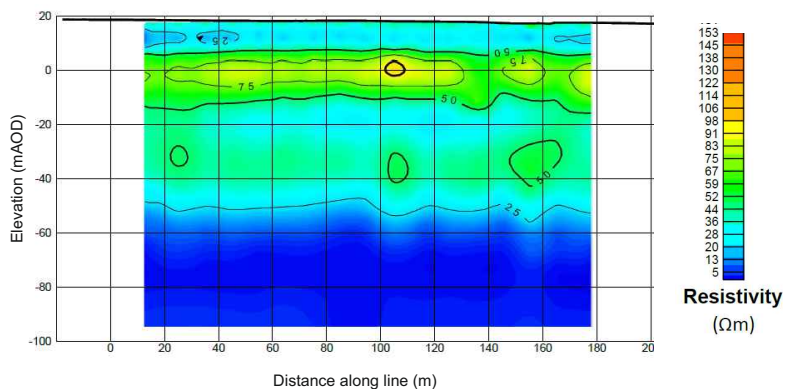
Unlike the resistivity tomography technique, TEM has the benefits that it does not require long electrode arrays and can be performed on a relatively small footprint of land subject to it accommodating the width of the transmitter loop (typically tens of meters in size).

The inversion of TEM sounding data determines a profile of conductivity (resistivity) with depth which is then interpreted in terms of a layered earth model with the principal parameters being layer thickness and layer conductivity. As with other profiling techniques, it suffers from the problem of non-uniqueness of solutions and so, benefits considerably from constraining information from complimentary ground investigation methods.

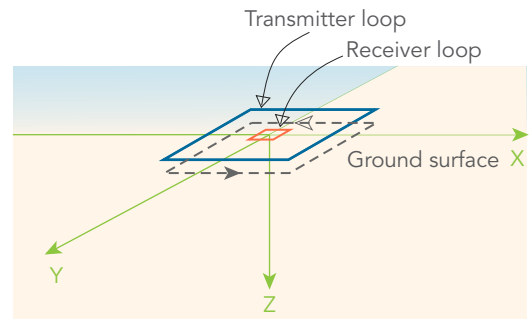
Lateral variation is shown by inverting measurements from successive measurement stations along a survey line. Results from a complete survey line are presented in cross-section form (see example **below**).



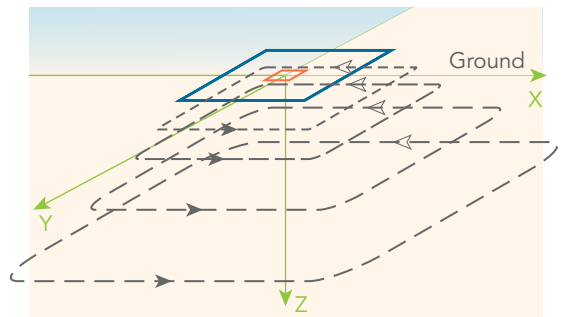
Layered model from inversion of a sounding curve at a single measurement location



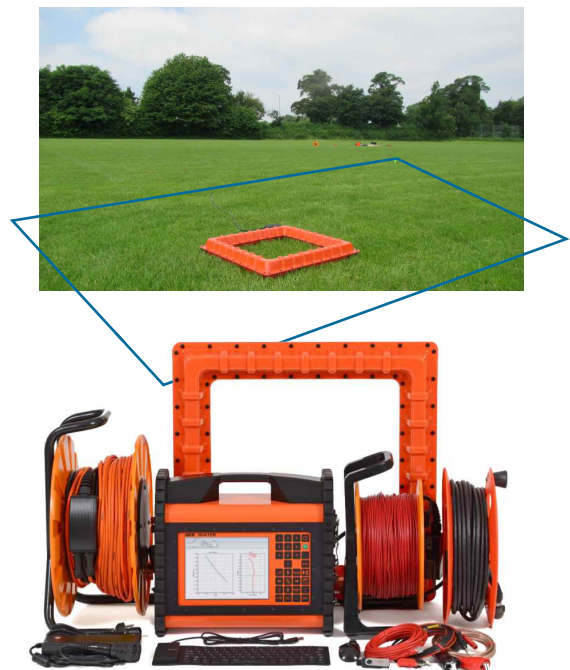
TEM data from multiple measurements along a survey line



a) eddy currents immediately after current turnoff



b) eddy currents at progressively later times



The ABEM WalkTEM system

Applications

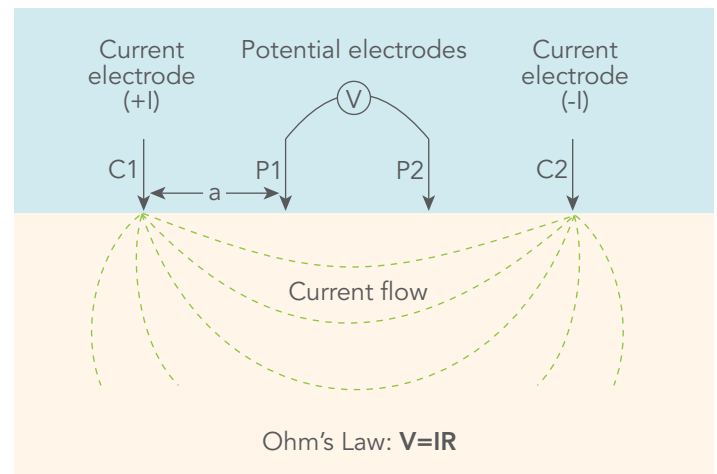
- ✓ Landfill Investigation
- ✓ Mapping and monitoring leachate plumes
- ✓ Mapping and monitoring of groundwater pollution
- ✓ Determination of depth to bedrock
- ✓ Locating sinkholes / cave systems
- ✓ Stratigraphic mapping
- ✓ Locating buried channels

- ✓ Mapping buried dykes and other ore bodies
- ✓ Locating fissures, faults and mineshafts
- ✓ Locating tunnels and large diameter buried utilities
- ✓ Landslide assessments
- ✓ Buried foundation mapping
- ✓ Time-lapse infiltration and moisture studies
- ✓ Cross-borehole tomography
- ✓ Soil corrosivity for pipeline assessment

Basic Theory

The electrical properties of the subsurface vary with the ground material, the presence and saturation level of fluids, and the presence of buried objects. Electrical techniques seek to describe the distribution of these properties as a function of depth and horizontal distance.

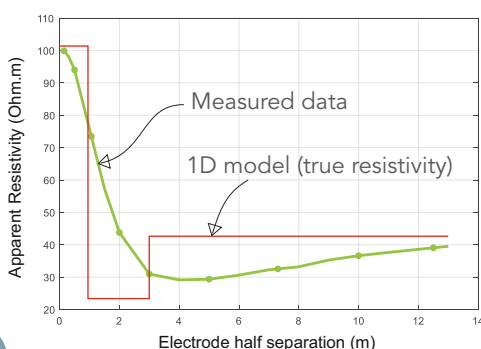
Measurements of ground resistance are made by introducing an electric current into the subsurface via two metal stakes (current electrodes) planted into the ground. The current passing through the ground sets up a distribution of electrical potential in the subsurface. The difference in electrical potential between two additional electrodes (potential electrodes) is measured as a voltage. Using Ohm's law, this voltage can be converted into a resistance reading for the ground between the two potential electrodes (see right).



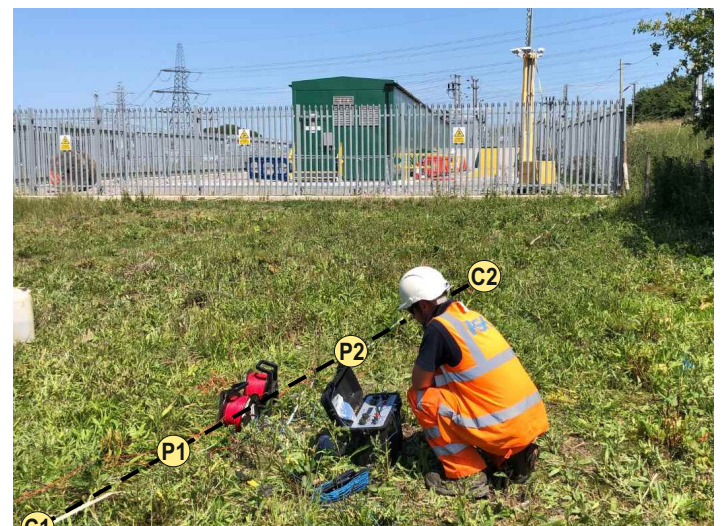
Vertical Electrical Sounding

The most basic of these methods to determine the electrical resistivity of the ground versus depth is vertical 1D electrical sounding (VES). The VES method is commonly used for groundwater exploration and engineering investigations such as earthing protection studies. The most common electrode arrangement is the Wenner array where four equally spaced electrodes are placed in a straight line and separated from each other by the same distance, a . The variation of the electrical properties of soil with increasing depth is explored by simply increasing the distance between the electrodes in the array over a fixed centre point.

The apparent resistivity is then plotted against electrode separation to produce a resistivity sounding curve (see below). Data is then inverted to generate a final resistivity model which provides the most representative characterisation of the soil layers at the test location.



Example VES data showing a three layer soil case



Deployment of VES equipment to test the soil resistivity to shallow depths to support a new substation installation

Thermal Resistivity

Soil thermal resistivity testing measures the capacity of the ground to conduct heat. This is important for the installation of new cables and pipes to ensure they do not overheat in the ground. Soil thermal resistivity testing is typically carried out in-situ within an inspection pit at the proposed depth of the installation with a handheld device attached to the probe which is inserted into the soil horizon. Readings are given in units of degrees C.m / Watts.



ELECTRICAL RESISTIVITY



Electrical Resistivity Tomography

Where information on the lateral variation of the ground materials is required the Electrical Resistivity Imaging (or Electrical Resistivity Tomography, **ERT**) technique is used. This allows the build up of a cross-sectional image of ground resistance from several meters to hundreds of meters deep.

A 2D ERT survey is produced by utilising a string of connected electrodes which are deployed along a straight line with an inter-electrode spacing of a . Once a measurement of ground resistance has been determined for one set of four electrodes, the next set of four electrodes is automatically selected and a second measurement of resistance is made. This process is repeated until the end of the line is reached. The line is then re-surveyed with an inter-electrode spacing of $2a$, $3a$, $4a$, etc. Each increase in inter-electrode spacing increases the effective depth of the survey (see **right**).

The measurements can be recorded in various array configurations that are selected based on the target of the investigation (see table **right**).

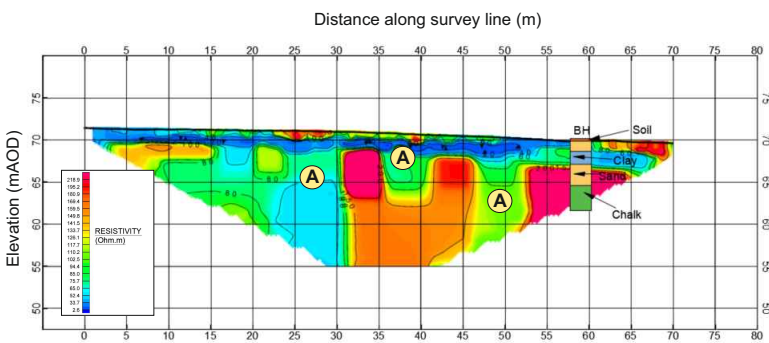
The measured resistance values are converted to values of apparent resistivity, ρ_a , (in ohm-metres) to produce a pseudo section of apparent resistivity. The resultant data are then processed using 2D inversion which generates a model of the true subsurface resistivity distribution (see example **below**).

The resultant section showing variations in resistivity is then interpreted to isolate anomalies and to outline the sub-surface geological structure. The use of ground investigation data can also help to constrain the models to provide a more robust interpretation.

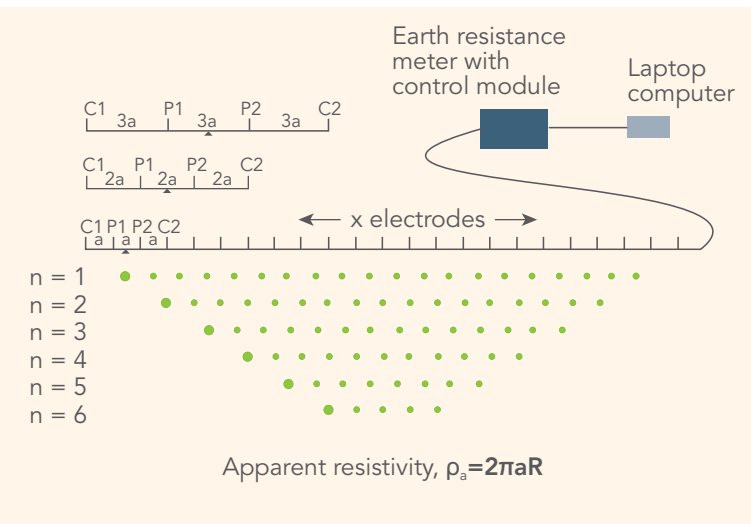
ERT Data Examples

Locating dissolution features

Below is an example of an ERT survey undertaken in an area at high risk of dissolution. Areas of clay filled vertical solution features were shown to correspond to discrete areas of lower resistivity in the deeper bedrock layer (marked 'A' in the section).



Example 2D resistivity model of a site with superficial deposits over chalk bedrock



Summary of common used arrays deployed in ERT surveys:

Array	Resolution	Depth	Pros/Cons	Applications
Dipole-Dipole	Best	Poor	Poor SNR; Quicker to acquire	Vertical structures (faults and dykes)
Wenner-Schlumberger	Better	Better	Better SNR; slower to acquire	Horizontal and vertical features
Wenner	Poor	Best	As above	Horizontal layers



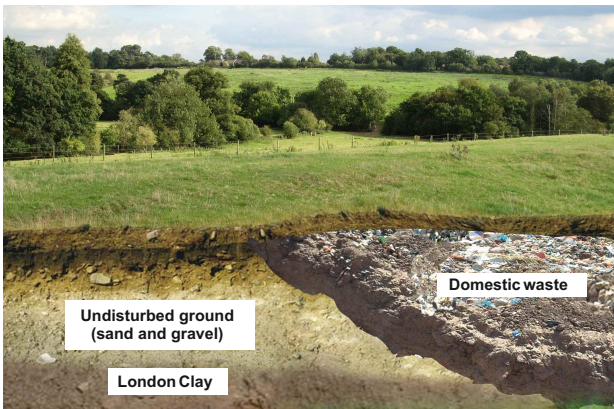
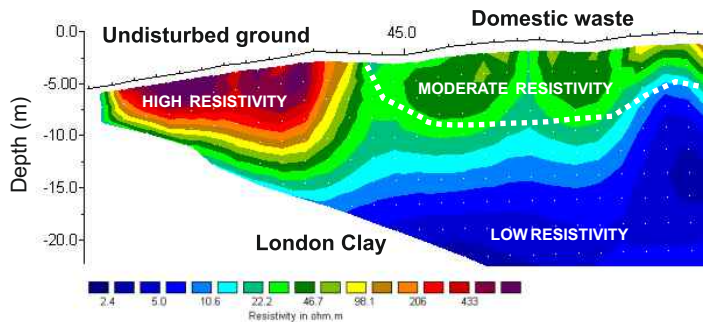
A typical electrical resistivity tomography survey comprises an array of electrodes placed along a line. The length of the line determines the depth penetration, and the electrode spacing determines the resolution.

ELECTRICAL RESISTIVITY



Delineating landfill extent and geometry

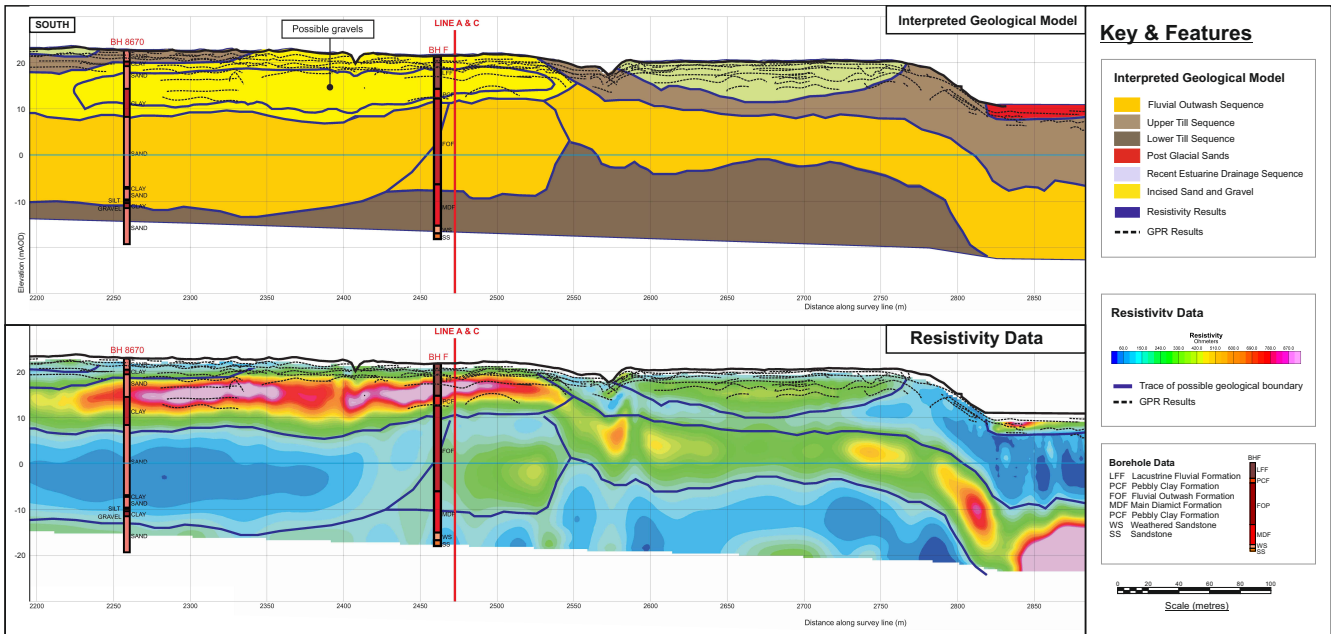
Below is an example of a survey undertaken across a closed landfill site filled with domestic waste. The ERT data provided information to the client on the extent of waste in the landfill and the thickness profile of its base.



Geological characterisation

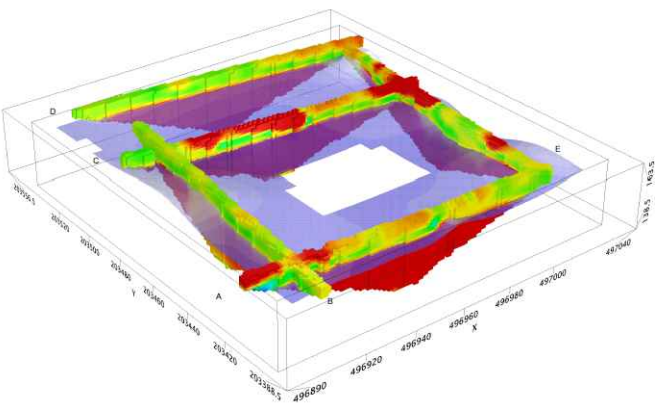
Below is an example of a survey carried out over a large coastal spit comprised of quaternary sediments to help characterise the internal structure of the spit in order to understand the future evolution and erosion of the coast at this location. As the spit was a protected SSSI the use of geophysics is also an ideal method of deployment due to its low impact/minimal disturbance.

In this example, the resistivity data were combined to produce interpretative geophysical models and cross sections. The ground model developed includes c.15m of glacial sediment above ordnance datum. Such detailed surveys can yield a great deal of information that would not otherwise be available to the engineer when borehole data is used alone.



Top of chalk bedrock interface

In the example (see image **right**) a number of resistivity survey lines were collected in two orientations across the site and combined in 3D to aid interpretation. By combining data in this way, it was possible to create surface meshes and isopleths representing the depth to chalk bedrock, water table and other interpreted layers.



Applications

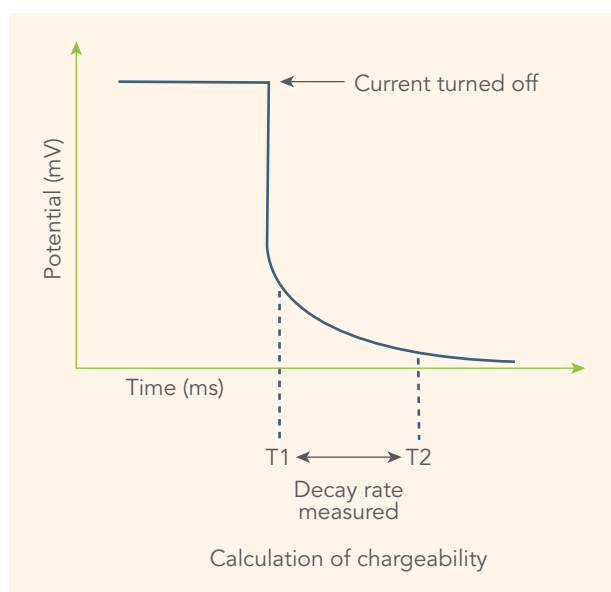
- ✓ Landfill Investigation
- ✓ Mapping and monitoring leachate plumes
- ✓ Mapping and monitoring of groundwater pollution
- ✓ Determination of depth to bedrock
- ✓ Locating sinkholes / cave systems
- ✓ Stratigraphic mapping
- ✓ Locating buried channels
- ✓ Mapping buried dykes and other ore bodies
- ✓ Locating fissures, faults and mineshafts
- ✓ Buried foundation mapping
- ✓ Time-lapse infiltration studies
- ✓ Assessment of aquifer heterogeneity

Basic Theory

Induced polarisation (IP) imaging is a complementary technique to electrical resistivity imaging and is concerned with the capacitance of the subsurface. The subsurface has the ability to both dissipate (resistance) and store (capacitance) the energy associated with an electric current flowing through it. Resistivity imaging measures how much energy is dissipated by the subsurface, whilst IP imaging measures how much energy is stored.

The capacitive action of the subsurface is evaluated by determining its chargeability. When a current is passed through the subsurface, a small charge is stored and the subsurface becomes charged. When the current is turned off, this charge decays with time and this decay is seen in the recorded potentials. By measuring the rate of this decay it is possible to calculate the chargeability of the subsurface.

Two materials that possess the same resistivity might possess contrasting chargeabilities. As such, IP imaging can provide additional discrimination of subsurface materials.



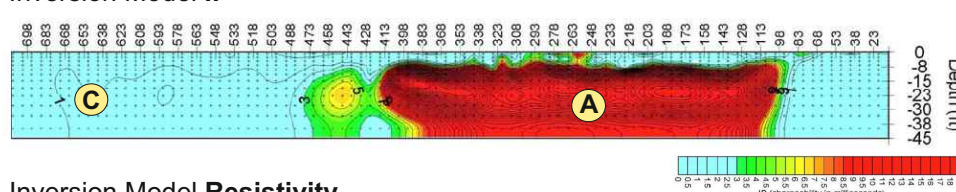
Data collection and presentation

The equipment used in IP surveys is similar to that used for electrical resistivity, with measurements being made of both the resistivity and chargeability of the subsurface. The survey typically comprises a number of ground electrodes in deployed an array connected to a computer controlled multi-channel receiver as shown **right**. Data from IP surveys is commonly presented as one cross-section for resistivity and one for chargeability. The data example **below** shows data from a resistivity/IP line across a buried landfill site. In this example the delineation of the landfill boundary from the IP survey is much more defined.

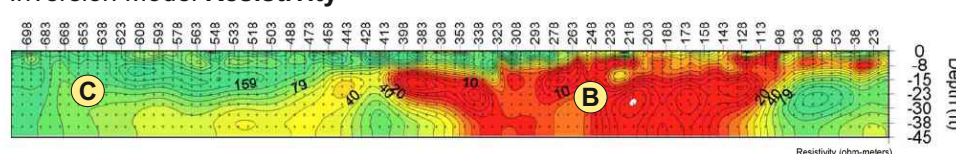


Deployment of electrical imaging equipment

Inversion Model IP



Inversion Model Resistivity



Features

- A** Well defined elevated IP response mapping extent of landfill waste
- B** Broad low resistivity anomaly correlates to IP data
- C** Undisturbed ground

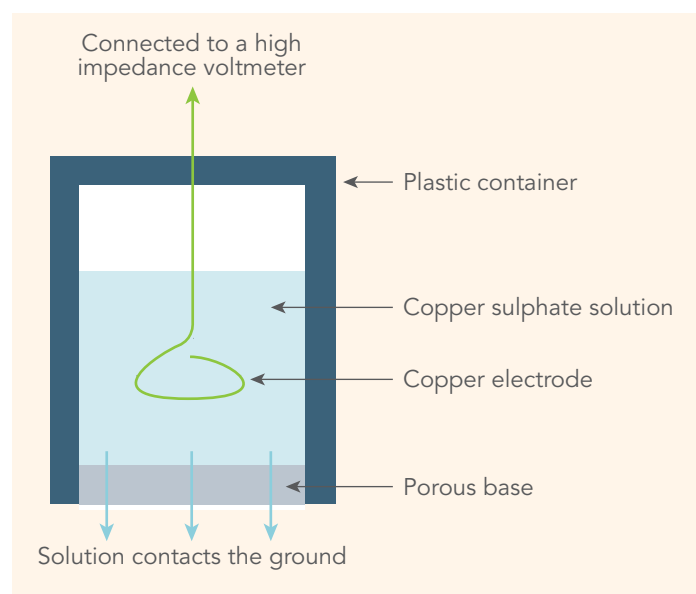
Applications

- ✓ Hydrogeological investigations (e.g. groundwater flow determination, contaminant transportation)
- ✓ Leak detection in reservoirs and dams
- ✓ Landfill delineation
- ✓ Geothermal surveys
- ✓ Locating massive sulphide ore bodies

Basic Theory

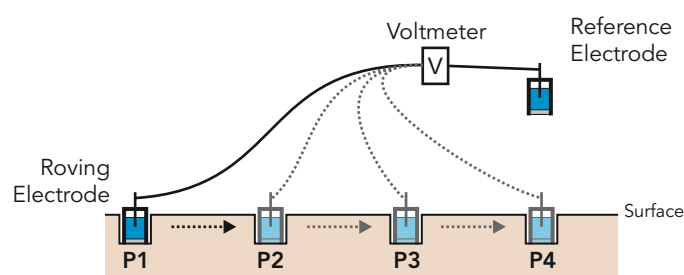
Self potentials (SP) are measurements of the difference in natural electrical potentials between two points on the ground surface. The natural electric currents responsible for these potentials may be generated by a number of different sources including groundwater flow, mineral deposits and chemical diffusion.

The magnitude of self potentials can vary from less than a millivolt to over one volt, and the polarity of the potential is a diagnostic factor in the interpretation of SP anomalies. Although there are many sources of self potentials, the common factor among them is groundwater. The potentials are typically generated by the flow of water, or by the involvement of water in natural chemical reactions.



Data collection and presentation

Measurements of self potentials are made with two non-polarisable porous-pot electrodes connected to a high impedance voltmeter. Traditional metal stakes, as used in resistivity surveying, cannot be used as they generate their own potential when they are inserted into the ground. Data is collected along a survey line (SP profiling) or across a grid to produce a contour map of self potential. The data requires little processing as most interpretations are based on qualitative analysis of profile shape, polarity and amplitude.



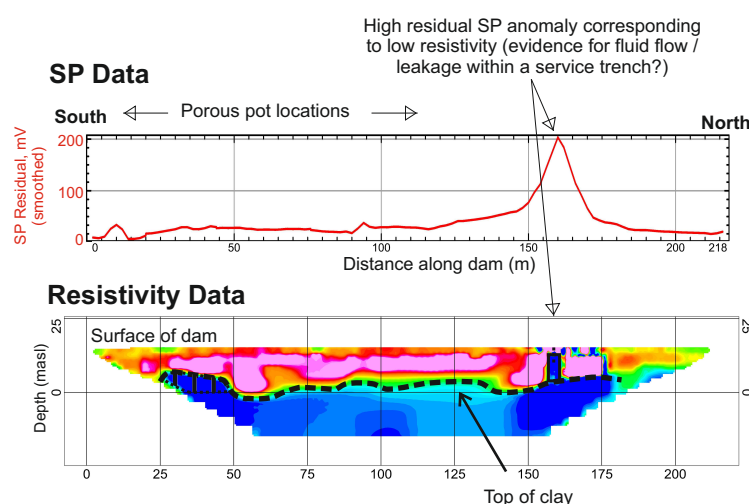
Two porous pot electrodes containing a copper sulphate solution are typically used throughout the survey. These are connected via copper wires to a voltmeter. The survey uses a reference electrode, held at a constant location, and a roving electrode.

Data Example

SP survey along a reservoir dam to identify potential areas of leakage

Self potential measurements can be used to identify the movement of electrical charge associated with the flow of water in the sub-surface.

In the example to the **right**, the technique was used to identify the possible presence of an area of saturation surrounding a possible pipe along a section of dam. The SP data (1D profile) was correlated with ERT data (2D profile) that was collected along the same line in order to add confidence to the interpretation of a leakage area.



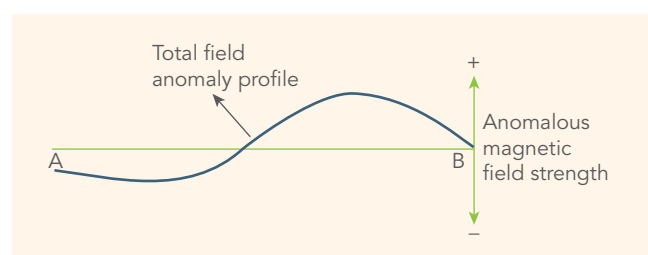
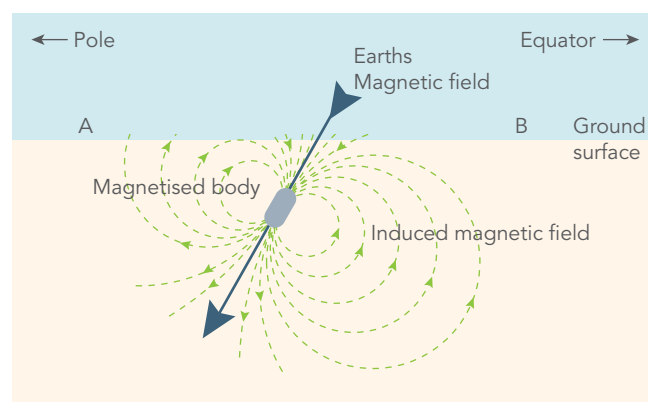
Applications

- ✓ Mapping underground storage tanks, buried drums, piles, reinforced concrete etc.
- ✓ Archaeological studies
- ✓ Mapping Unexploded Ordnance (UXO)
- ✓ Pile and foundation detection
- ✓ Mineral exploration (dykes and ore body mapping)
- ✓ Locating landfills and buried infill
- ✓ Detection of underground pipes and other utilities
- ✓ Detection of mineworkings (i.e. reinforced capped shafts)

Basic Theory

Magnetic surveying is a passive method based on the measurement of localised perturbations to the Earth's magnetic field caused by the presence of buried ferrous targets (e.g., pipes, cables, drums, military ordnance etc).

Gradiometry surveys, which determine the vertical gradient of the magnetic field, are increasingly common in environmental/engineering site investigations as they are particularly sensitive to the near-surface. Magnetic surveys can be conducted with a wide range of magnetometers, which can measure the amplitude of the field to within 0.01nT.



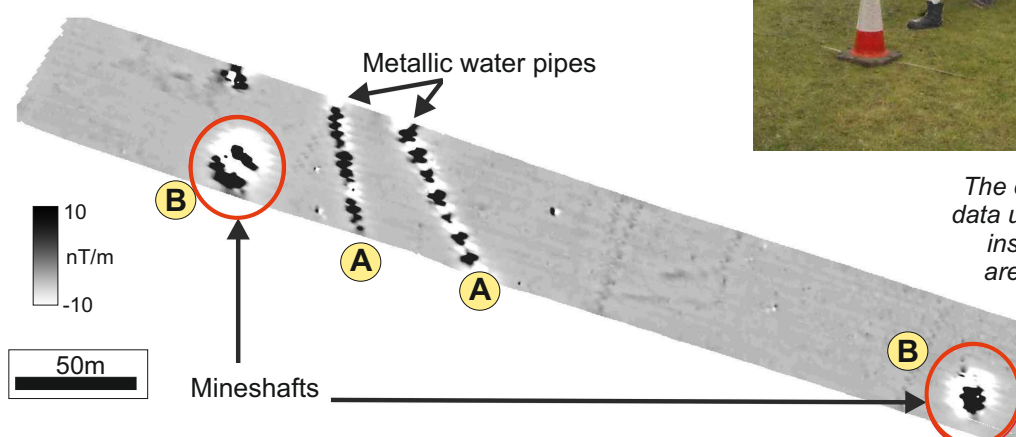
Data Presentation

Typically, data is collected in a systematic manner across a field site and then presented as a contoured map (in units of nT or nT/m) which can be interpreted to produce a map of the subsurface. The amplitude and shape of an individual anomaly will reflect the dimensions, orientation and magnetic susceptibility of the buried target.



Data Example

Magnetic surveying is useful in many situations, in particular to detect buried manmade metallic objects. In this example **below** of magnetic gradient data recorded along a proposed cable route, the survey has revealed the location of two buried utilities (A), and two circular features (B). The circular features were further investigated by intrusive means and found to be mineshafts capped with reinforced concrete.



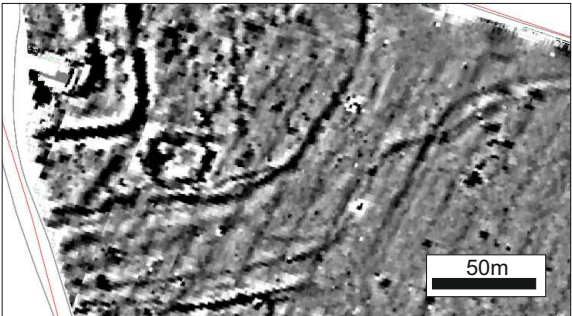
The collection of magnetic gradiometer data using a dual sensor Bartington 601 instrument. In this instance traverses are made in discrete grids across the survey area on interest.

Data Examples

Magnetic Gradiometry

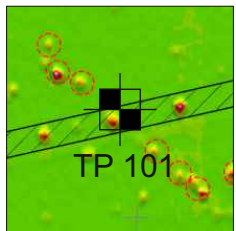
1 Archaeological evaluation using magnetics

In the example **right**, the data shows linear features such as walls together with circular features interpreted as ring ditches. These areas of particular archaeological potential were identified for targeted follow-up surveys prior to further site development.

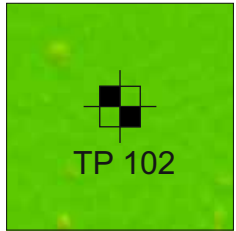


2 Locating buried Unexploded Ordnance (UXO)

Buried and unknown UXO can in certain locations in the UK present land developers with a real threat to workers and the public. The most common methods used to locate UXOs in the shallow sub-surface are surface magnetometer surveys (see below left and data to right), or by probing boreholes (below centre) to check deep UXO are not encountered.



Multiple buried metal objects detected in the ground

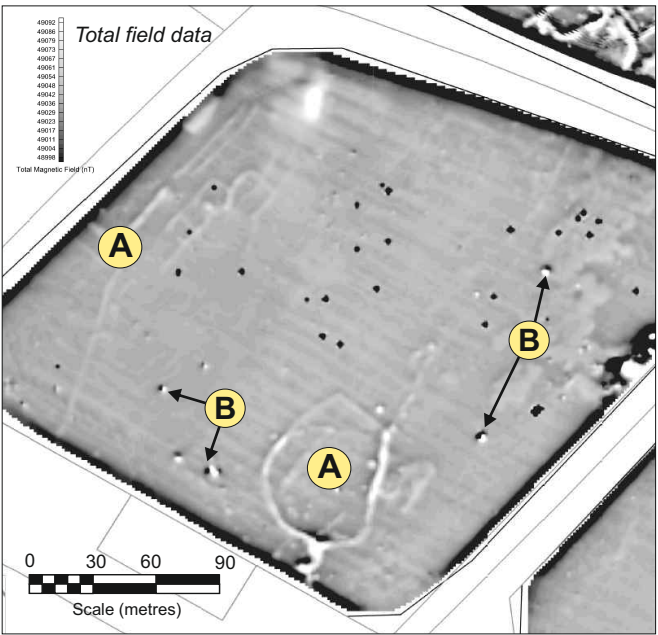


'Cleared' area with minimal surface response

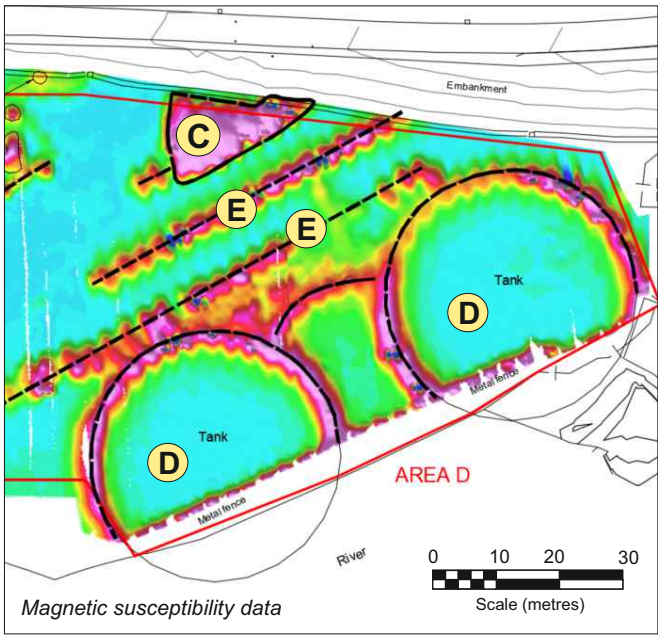
Example magnetic susceptibility data across 50m x 50m area. Warm colours show high response.

3 Magnetic anomalies locating buried obstructions

- A** Anomalies with regular geometric shapes indicative of manmade structures of archeological significance
- B** Small, discrete, dipolar response indicative of metal containing objects such as possible UXO



- C** In-situ building foundation outline demarked by high amplitude instrument response
- D** Circular foundations of former USTs
- E** Linear response from buried utilities



Applications

- ✓ Cavity detection (e.g., bomb shelters, collapsed tunnels, old mineworkings, natural cave systems, sinkholes and other solution features etc)
- ✓ Density determination
- ✓ Mineral exploration
- ✓ Locating buried tanks and reservoirs

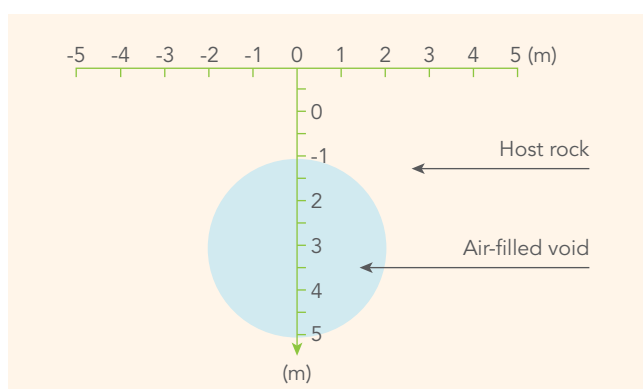
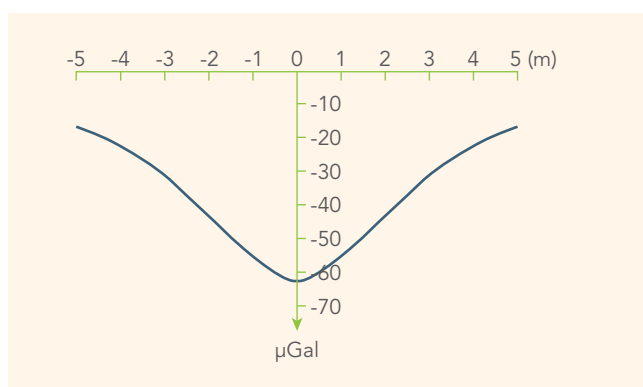
Basic Theory

Different subsurface materials have different bulk densities. Microgravity surveys seek to detect areas of contrasting or anomalous density by collecting surface measurements of the Earth's gravitational field.

A gravity meter is a highly sensitive instrument that measures the *acceleration* due to gravity. When positioned above a dense material it records the acceleration (g) as a relative high (a *positive gravity anomaly*). When positioned above a low density feature (e.g. an air filled cavity) a relative gravity low (or *negative gravity anomaly*) is recorded.

*The diagram to the **right** shows a negative gravity anomaly arising from an air-filled void (sphere) with a radius of 2m and a depth to centre of 3m.*

The density of the host rock = 2.5 Mg/m^3



Data Acquisition

Gravity anomalies arising from natural or manmade subsurface features such as voids and cavities are superimposed on much larger variations due to height, latitude and regional geological variations. In order to isolate the subtle signal of interest, careful data acquisition and processing is required.

For a successful survey it is imperative that the highest quality of data is collected. Micro-gravity surveys are particularly sensitive to the data collection methodology which must be carefully tailored to the site and environmental conditions, as well as being appropriate to the survey target. Survey data are typically acquired in a grid of points.



Data acquisition with a Scintrex CG-6 Gravimeter

Data Processing and Presentation

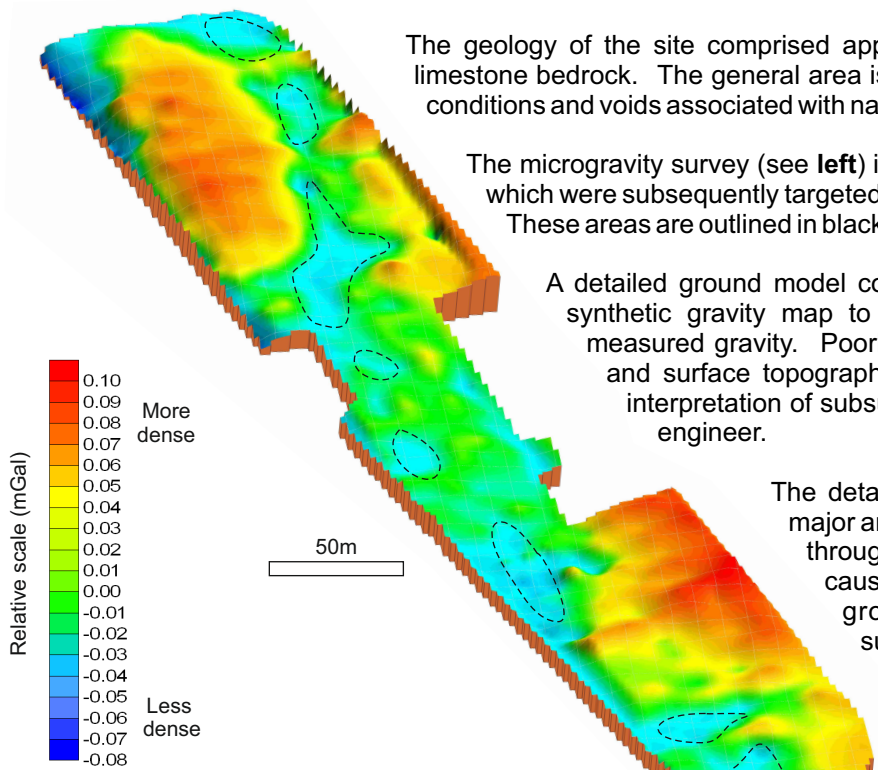
Data recorded on site should include accurate position and height measurements for each recording station, and number of readings at each station from which to evaluate data quality, and a number of repeated recording stations at known time intervals from which to determine the repeatability of the results. Sufficient QC data are required to correct for factors such as earth tides, instrument drift, and other time variant effects. Corrections are changes in the Earth's

gravitational field (known as drift), variations in latitude elevation, local terrain and regional geology. The result is a *residual microgravity map* from which both qualitative and quantitative interpretations may be derived.

An accurate micro-gravity anomaly map can be used to calculate the location, depth density contrast and therefore volume of the subsurface feature.

Data Examples

1 Microgravity survey along the proposed route of a bypass to detect voids & poorly consolidated ground



The geology of the site comprised approximately 14m of glacial till overlying limestone bedrock. The general area is known to be susceptible to poor ground conditions and voids associated with natural cavities in the limestone.

The microgravity survey (see **left**) identified areas of low subsurface density, which were subsequently targeted by a conventional borehole investigation. These areas are outlined in black on the map.

A detailed ground model constructed from borehole data allowed a synthetic gravity map to be calculated for comparison with the measured gravity. Poorly consolidated ground, depth to bedrock and surface topographic effects could be isolated and a clear interpretation of subsurface conditions presented to the project engineer.

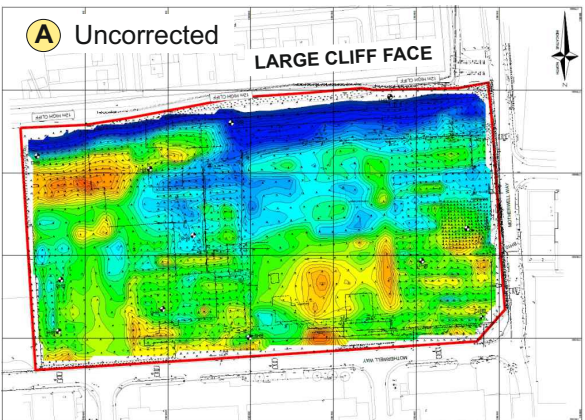
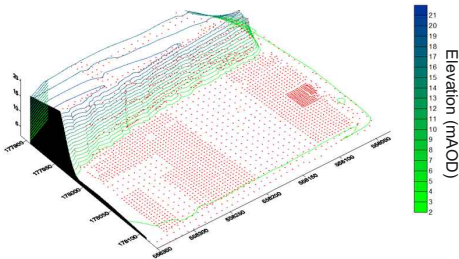
The detailed borehole investigation of one of the major anomalies identified in this data set allowed, through some simple and quick calculations, a cause and effect link to be proven between ground conditions and the microgravity survey results.

A Bouguer anomaly map of the survey area. Regions of poorly consolidated ground are outlined in black.

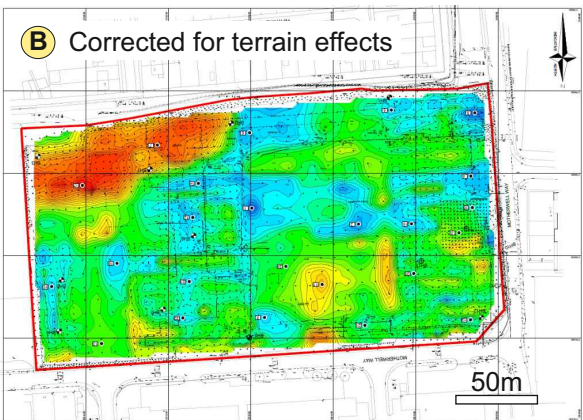


2 Microgravity survey of former chalk works showing terrain effects from large variations in site topography

In this example (see site as elevation plot **right**) the gravity survey comprised a large flat open area with over 1000 unique gravity measurement points. Although the site topography was flat, there was a significant cliff feature up to 20m in height to the edge of the site. This caused measurable effects in the observed gravity and required the terrain effects of the cliff to be calculated and removed. RSK have developed specialist forward modelling algorithms from various research projects (see www.rsksigma.co.uk for more details). The microgravity data **below left** shows the data before the terrain effects of the cliff have been accounted for (note the large negative response along the toe of the cliff). The data **below right** shows the same data corrected for the terrain effects.



Correction



Applications

- ✓ Stratigraphic mapping
- ✓ Estimation of depth to bedrock
- ✓ Estimation of depth to water table
- ✓ Predicting the rippability of specific rock types
- ✓ Locating sinkholes
- ✓ Landfill investigations
- ✓ Geotechnical investigations

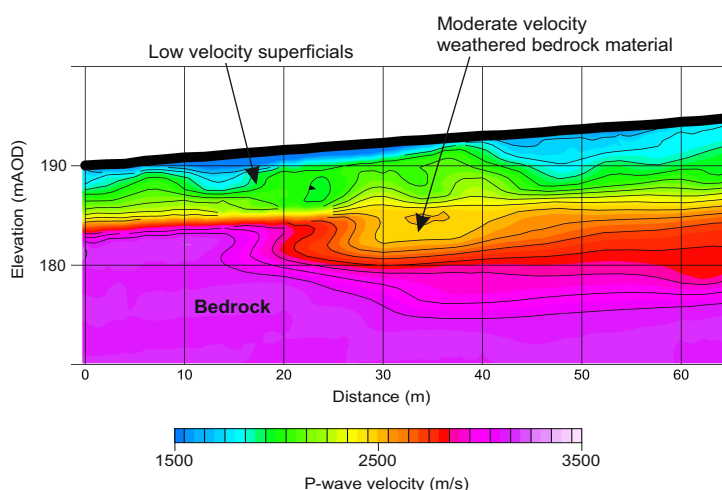
Basic Theory

The seismic refraction technique is based on the refraction of seismic energy at the interfaces between subsurface/geological layers of different velocity. The seismic refraction method uses very similar equipment to seismic reflection, typically utilising geophones in an array, and a seismic source (shot).

The schematic diagram (**below right**) illustrates the path of seismic waves propagating from a source at the surface. Some of the seismic energy travels along the surface in the form of a *direct wave*. However, when a seismic wave encounters an interface between two different soil or rock layers a portion of the energy is *reflected* and the remainder will propagate through the layer boundary at a *refracted angle*.

At a *critical angle* of incidence the wave is *critically refracted* and will travel parallel to the interface at the speed of the underlying layer. Energy from this critically refracted wave returns to the surface in the form of a *head wave*, which may arrive at the more distant geophones before the direct wave.

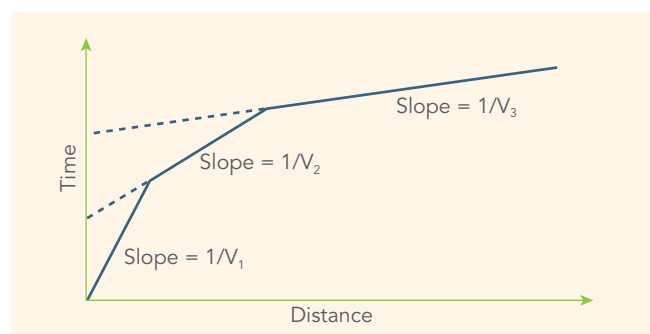
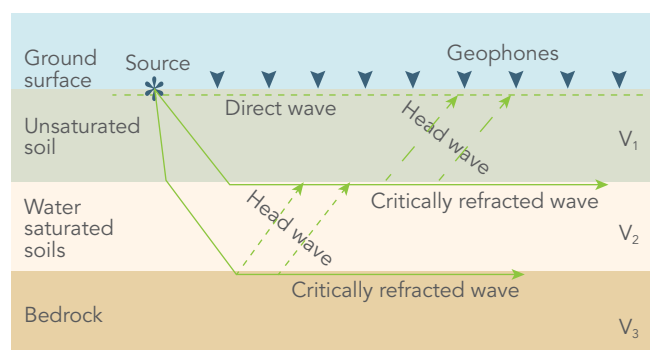
By picking the time of the first arrival of seismic energy at each geophone, a plot of travel-time against distance along the survey line can be generated. This type of graph is shown in the schematic to the **right**. The gradients of the lines in this type of plot are related to the seismic velocity of the subsurface layers. The final output is a velocity/depth profile for the refractors as shown **below**.



Seismic velocity cross-section showing the bedrock profile beneath a route of a proposed pipeline.



Seismic refraction setup with a series of geophones



Another approach available for the interpretation of refraction data is the modelling and inversion of the acquired seismic velocities. By modelling the paths taken through the subsurface by the seismic energy, or 'ray tracing', the thickness of each layer in the model can be adjusted in an iterative manner until a solution is achieved. This produces a cross-sectional velocity model of the subsurface. Borehole records can further calibrate the data to provide levels of the subsurface layers across the survey line.

Data Examples

Defining Geological Boundaries

This seismic refraction survey locates the geological boundaries between layers. The most common application is the detection of the top of bedrock as shown in the example below on an estuary site in Somerset where variable superficial deposits were suspected. **Figure 1** shows the typical equipment used in this type of survey. **Figure 2** shows a typical arrival

time plot. **Figure 3** displays a colour cross section of the ground along the survey line reflecting the associated velocities. In this case a simple 2-layer model is suggested by the travel time data, with layer velocities in the lower bedrock layer of 1.9km/s. **Figure 4** shows the interpreted boundary which is further confirmed by borehole information.

1 Data acquisition stage

Here an accelerated weight-drop seismic source was deployed as part of a survey in Somerset (line shown in blue)

2 Data processing

First arrivals are picked from every shot record and analysed to determine the number of seismic velocity layers

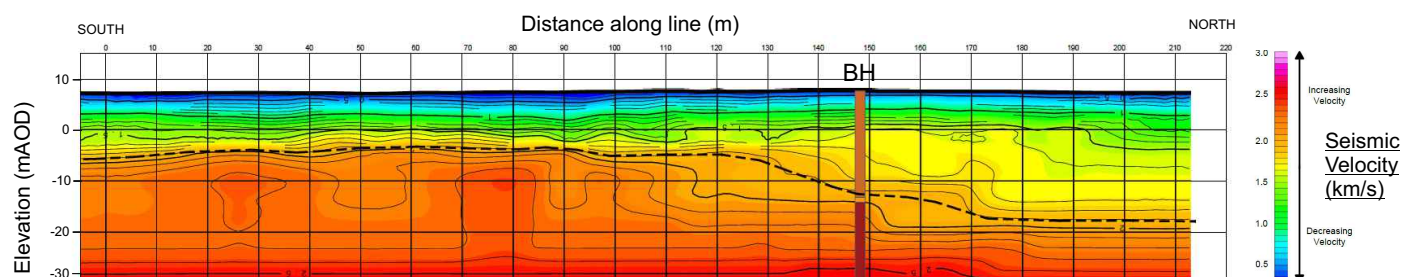
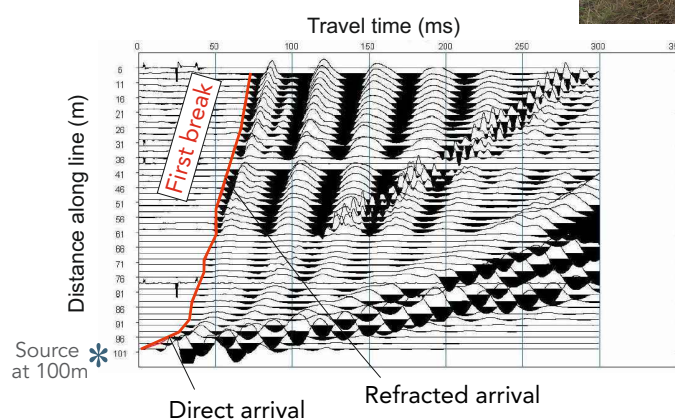


* Source

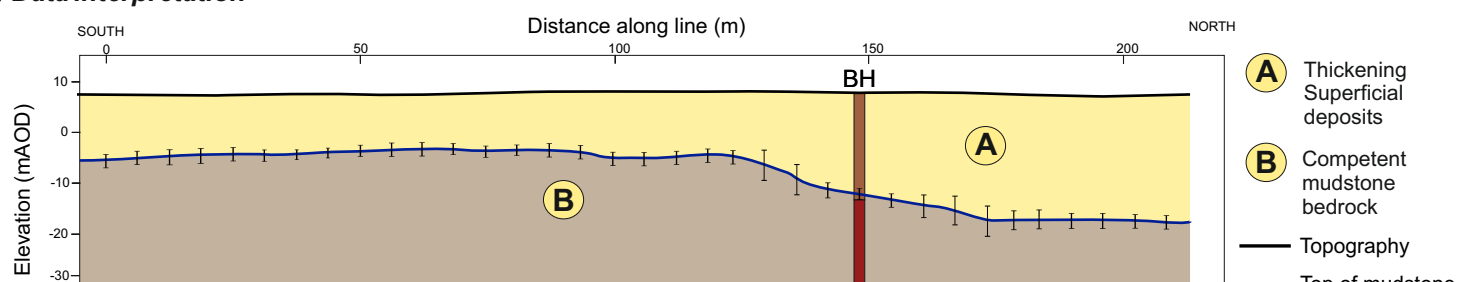
Geophone array

3 Data analysis

Depth profiles for the seismic velocity layers are produced from inversion of first-arrival data generating a subsurface tomographic structure model



4 Data interpretation



Applications

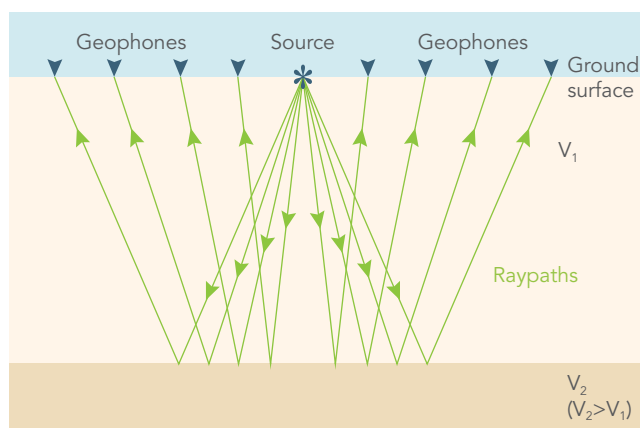
- ✓ Stratigraphic mapping of Quaternary deposits
- ✓ Estimation of depth to bedrock
- ✓ Hydrogeological mapping
- ✓ Voiding and disturbed ground associated with dissolution

Basic Theory

Elastic energy injected into the ground by an impulse or vibrating source will propagate through the ground as elastic or seismic waves. Where a wave encounters a contrast in acoustic impedance (determined by the elastic properties of a material and its density) a proportion of the wave energy will be reflected (see **right**). Recordings of the seismic waves reflected back to the surface can then be processed to construct an image representative of the subsurface.

Any geological boundary can represent a contrast that would generate a reflection. As such the technique can provide detailed information on the geometry of sedimentary sequences, structural faults, igneous intrusions and evaporite deposits. Dependent upon the nature of the data additional information can be derived from the seismic velocity absorption or anisotropy of individual units.

The technique is likely to be useful in a wide range of geological environments because of its ability to produce a high resolution image of the subsurface that can be tied directly to a geological model. Details of individual geological units can be traced across the survey volume, and structural features can also be mapped. In addition, advanced processing can be undertaken to obtain other characteristics of the seismic waves that can be linked to specific physical properties of the rock mass such as fracture density and orientation, porosity and rock mass strength. These wave characteristics are called “attributes”, and examples of seismic attributes include the amplitude, frequency or phase of the seismic wave.



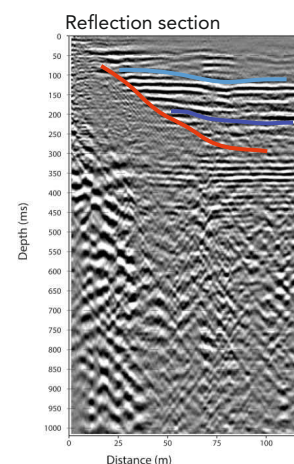
The ability of a seismic data set to image a geological feature is largely a function of the frequency content of the seismic data, with a higher frequency content leading to greater resolution. The frequency content of a seismic data set is controlled by the seismic source type. Large explosive charges have higher energy low frequencies than smaller explosives. Frequency sweep sources using electromagnetic vibrators (see image **below**) rely on the control provided by a known source wave containing a range of frequencies and the frequency content will depend on the system and configuration deployed. Higher frequencies provide higher resolution, but are more quickly absorbed by the earth and so have limited depth penetration. The theoretical resolution of features within a data set is equal to one quarter of the wavelength of the seismic signal. In practice other factors affect the signal to noise ratio and reduce the resolution achieved.



Hammer source for P waves.



Deployment of tracked vibrating source.



Exploration up to 100m is possible

MULTICHANNEL ANALYSIS OF SURFACE WAVES **RSK**

Applications

- ✓ Stratigraphic mapping and depth to bedrock
- ✓ Anomaly detection (e.g. voids and tunnels)
- ✓ Characterisation of poorly consolidated or weak ground
- ✓ Soil stiffness and ground improvement verification

Basic Theory

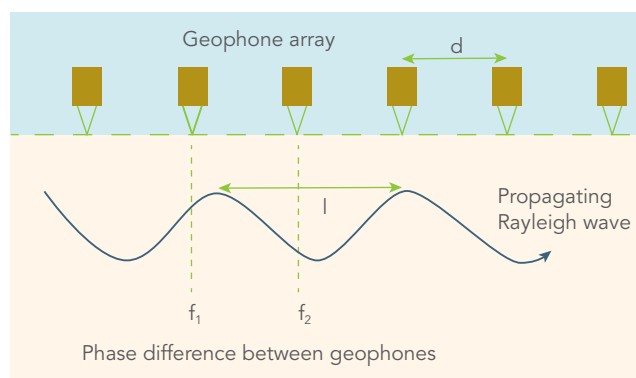
Multichannel Analysis of Surface Waves (MASW) surveying is an active and passive method based on the measurement of Shear Wave Velocity (V_s) which is an indicator of the ground stiffness. Therefore surface waves allow the measurement of the variation in small strain ground stiffness (G_{max}) with depth.

The surface wave technique is based upon the dispersion, or change in phase velocity with frequency (and therefore wavelength), of a seismic wave propagating through the subsurface. Longer wavelengths penetrate to deeper depths whilst shorter wavelengths are sensitive to the elastic properties of shallower layers. Surface wave dispersion is significant in the presence of velocity layering, which is common in the near-surface environment.

Although there are other types of surface waves, the term "surface wave" when used in the SASW (Spectral Analysis of Surface Waves), MASW (Multi-channel Analysis of Surface Waves), or MAM (Microtremor Array Measurement) context has come to mean the Rayleigh wave. Since the Rayleigh wave is the dominant component of ground roll, it is also referred to as "ground roll" (see **above**). There is no difference in the Rayleigh waves generated by different systems, but the method used to generate and record the waves differs.



A series of geophones arranged along a MASW survey line



Data Acquisition

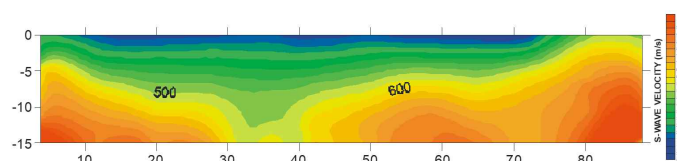
Two different methods of acquisition are available for the collection of surface wave data.

The first method developed was Continuous Surface Wave (CSW), which employs a single transmitter that generates a continuous vibration with two or more receivers (geophones). Data is collected over a range of frequencies to vary the depth of investigation.

The MASW method system operates by using an impulsive source and multiple receivers (multi-channel) along a much longer survey line. An active source is used (typically a hammer blow) together with using the "background" seismic noise already present. Using specialist inversion software, the results from active and passive sources are combined.

Recorded MASW data are transformed into a plot of phase velocity vs. frequency - known as a dispersion image - in order to determine the wavelength of each frequency present, and also the velocity at which that frequency propagates. In processing, as a first approximation the velocities from each profile can be assigned to depths equal to one third of the wavelength.

Ground models are typically built initially as a 1D stiffness profile for each adjacent pair of geophones. Adjacent profiles are then merged to give continuous cross section image of the shear velocity of the subsurface to form a 2D ground model (see **below**). Similarly, a number of adjacent cross-sections can be combined to produce a 3D image.



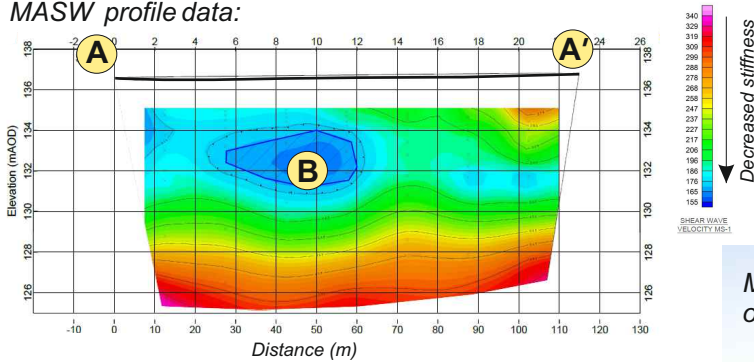
2D section derived from MASW data showing lateral and vertical variation in measured velocities

Data Examples

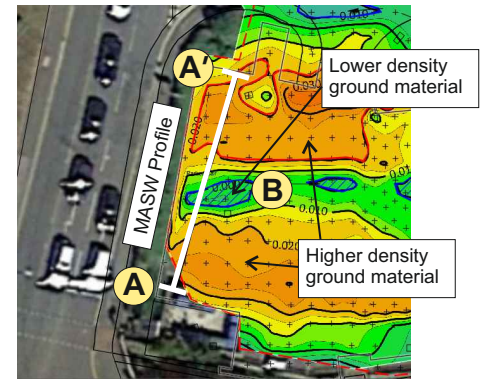
Detection of weak zones and voids

In this example, MASW and microgravity were used to successfully identify areas of potential voiding or low density loose ground at a former mill site in Derbyshire, UK. Near surface low velocity anomalies were observed in MASW profiles recorded at the site (See labelled B below). These corresponded to the location of negative microgravity responses (see right). Deploying multiple geophysical methods allowed a more robust interpretation of the ground model at the site.

MASW profile data:



Microgravity plan view data:



MASW data (together with other complimentary methods) can provide continuity of information and allow effective targeting of subsequent borehole or probing to confirm the origin of the anomalies present.

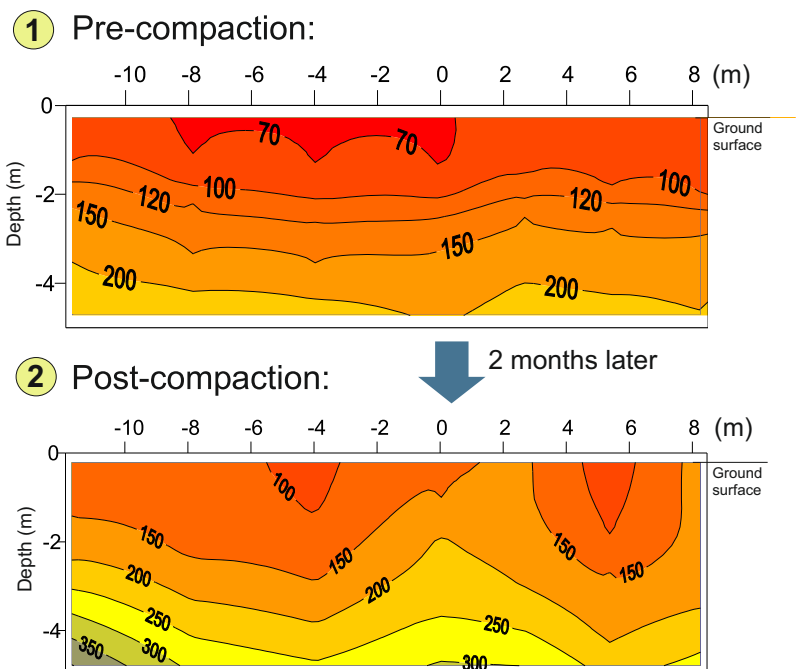
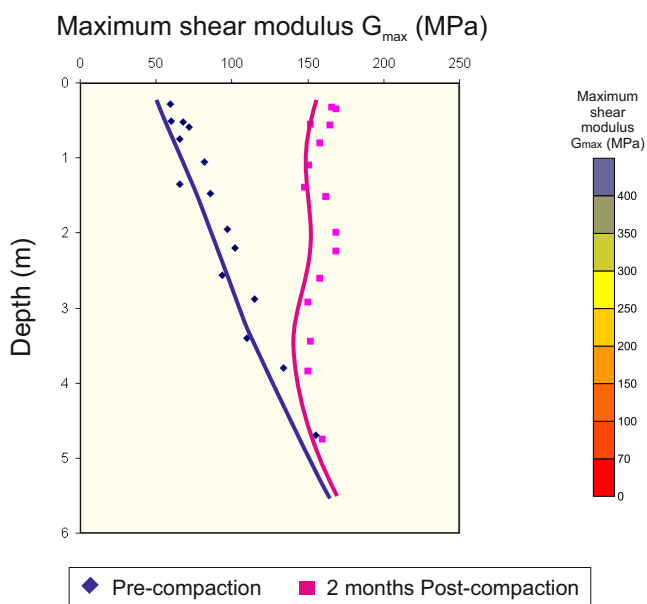
Ground improvement monitoring

In this example time lapse MASW was used to assess the change in ground stiffness after ground-improving compaction had been carried out prior to the construction of a road.

Below left is a graph displaying the maximum shear modulus of the ground versus depth. The results show a clear and measurable improvement after compaction. The two diagrams **below right** show a 2-dimensional stiffness profile from the same site, before and after ground improvement.



MASW testing can be carried out on soils of many types, including hardstanding.



Applications

- ✓ Existing pile and foundation analysis
- ✓ Estimation of depth to bedrock
- ✓ Locating solution features and voids
- ✓ Geological and hydrological mapping
- ✓ Dynamic rock moduli
- ✓ Foundation design for dynamic loads

Geophysical Techniques Available

Borehole geophysics takes advantage of the higher spatial resolutions at depth afforded by deploying instruments vertically down a borehole. Techniques available include:

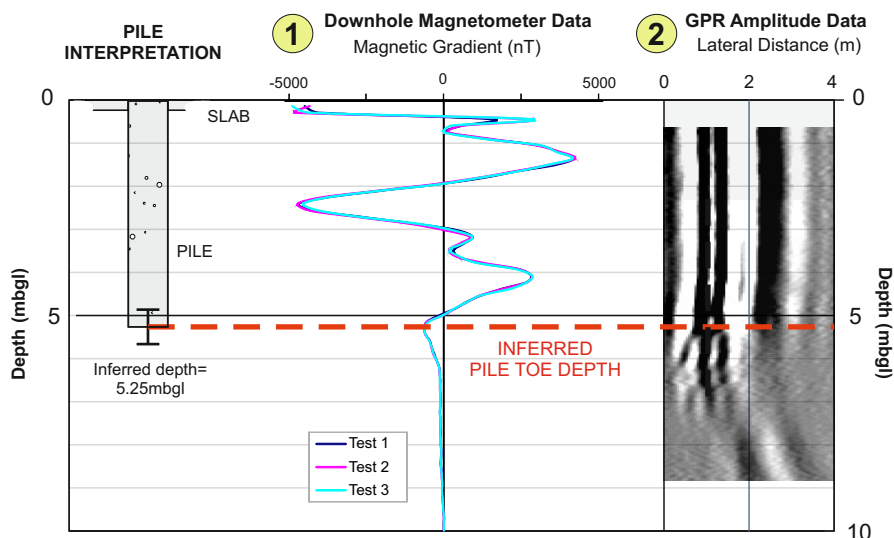
- ✓ Ground Penetrating Radar (GPR)
- ✓ Magnetics
- ✓ Parallel Seismic Testing
- ✓ Downhole Seismic Testing
- ✓ Crosshole Seismics
- ✓ Resistivity

The techniques shown here typically operate in the same manner as they would on the surface, with the advantage of providing high resolution data at depth. Sensors that measure different properties are lowered into the borehole to collect continuous or point data that is graphically displayed. They can, if required, be used in various combinations.

Survey examples

Pile toe depth and reinforcement length analysis with Borehole Magnetics and GPR

A slimline Ground Penetrating Radar (GPR) antenna (**right**) can be used down a borehole to locate buried foundations or map fracture zones and voids. In this example, downhole GPR was used together with a downhole magnetometer probe (**below right**) to locate the depth of pile reinforcement length and the toe depth of the piles. Below is a magnetic and GPR example from a borehole which clearly marks the base of the metal reinforcement in the pile by the sudden drop in the measured magnetic field strength, and by the termination of a high amplitude reflector in the GPR data.



Borehole geophysics requires the use of an existing or newly prepared borehole or array of boreholes in order to carry out the testing. RSK can provide borehole drilling and installation services as part of the overall testing package.



A Borehole GPR probe being lowered into the hole.



Acquisition of magnetic data down a borehole using a vertical gradient magnetometer probe.

Parallel Seismic Testing to determine the length of buried piles

Many cities and towns world-wide, have been built over numerous times. The ground is often full of old foundations. Therefore the re-use of old piles is becoming increasingly necessary. As part of the investigation of existing piles to inform calculations of load bearing capacity, parallel seismic testing can be used successfully to characterise the length and geometry of piles.

The depth of a pile can be determined from the change in velocity of a compressional p-wave induced at the toe of the pile. As shown below, typically, the wave travels rapidly through the pile and then slows in the surrounding ground.

The parallel seismic technique requires a borehole to be drilled parallel, and close to, the target pile (ideally

within 1.5m). The borehole should extend to a depth (ideally at least 3m) below the anticipated base of the pile. Typically the borehole has an internal diameter of circa 7-10cm, is plastic lined, and is filled with water to provide acoustic coupling with the immersed hydrophones. Some portion of the structure that is connected to the foundation must be exposed for the hammer impacts.

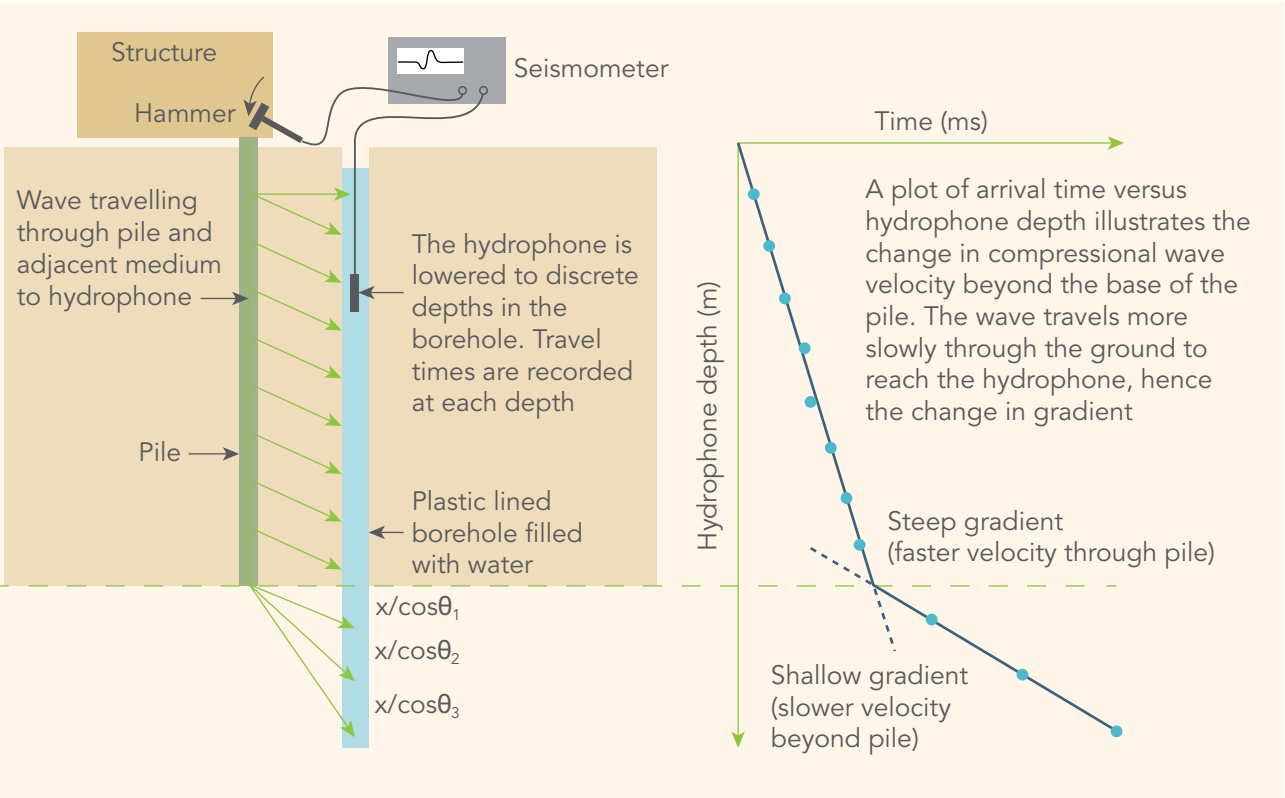
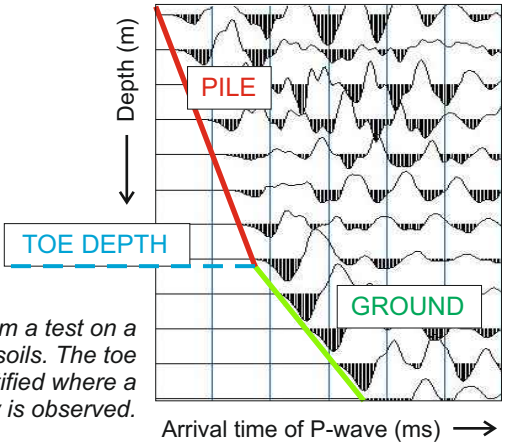
The hydrophone is lowered to discrete depths. At each depth a recording is made of the energy from a hammer blow. An evaluation of the travel time of this pulse down the pile and across the intervening material to the hydrophones permits an assessment of pile length to be made.

The parallel seismic method is generally used in combination with downhole magnetics and GPR (see previous page) as pile toe depth can sometimes differ from the actual length of reinforcement in a pile.



The parallel seismic method being used within an adjacent borehole to ascertain information on the depth of a sheet pile. Note access to the top of the pile is required.

Example PST data from a test on a concrete pile in saturated soils. The toe depth of the pile (blue) is identified where a marked increase in velocity is observed.

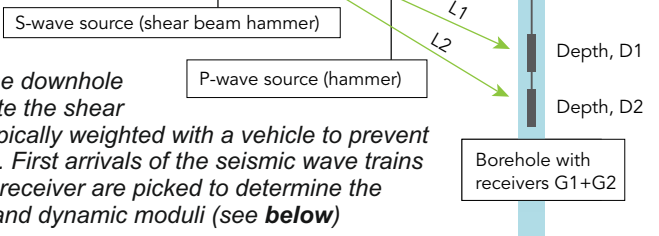


Borehole seismic surveys are used to obtain in situ properties of soil and rock strata and are often used as part of a comprehensive geological and geotechnical investigation.

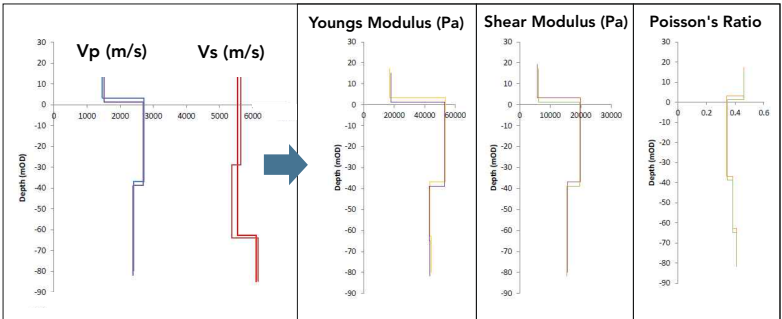
Downhole Seismic Testing

In downhole seismic testing, direct and interval measurements of the velocities are determined from arrival times of compression (P-) waves, and horizontally orientated shear (S-) waves which are generated on the ground surface and travel down to an array of vertically installed receivers in a borehole which is advanced through soil or rock.

The sources are offset horizontally from the top of a cased borehole (see **right**). P-waves are typically generated by a hammer blow whilst SH-waves are generated using a 'shear-beam' with hammers on either end to produce two oppositely polarised energy trains. One or two receivers are typically used in the borehole and positioned at increasing interval test depths. The recording system measures the travel time of the wave train between the source and receivers from which velocities are calculated for each depth, known as the direct method, or between receivers, called the interval method. Inversion algorithms are used to provide more robust velocity profiles with depth. When combined with rock density information, this allows the determination of Shear and Youngs Modulus and Poisson's Ratio.



Above: The downhole set-up. Note the shear beam is typically weighted with a vehicle to prevent movement. First arrivals of the seismic wave trains from each receiver are picked to determine the velocities and dynamic moduli (see **below**)

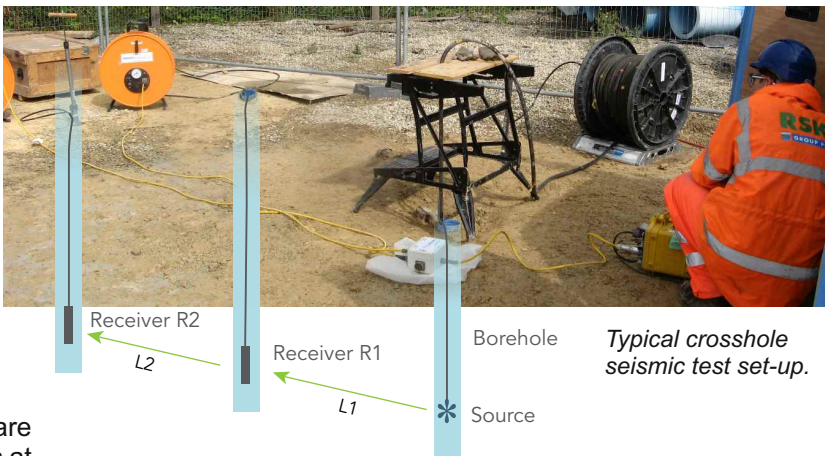


Crosshole Seismics

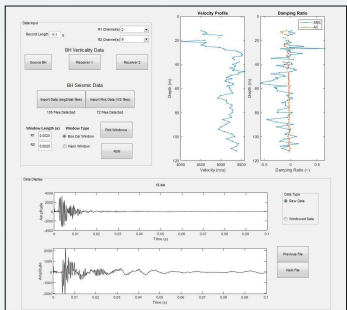
The cross-hole test is based on the detection of seismic waves generated in one borehole by receivers located in one or more adjacent boreholes. Analysis of the first arrival times of the seismic waves over a distance from the source can provide information on the distribution of the elastic properties of the subsurface between boreholes.

At selected depths down the source borehole, a borehole seismic source is used to generate a wave train. Downhole receivers are used to detect the wave train in offset boreholes at a spacing of between 3m and 10m. The distance between the boreholes at the test depths is measured using a borehole deviation survey.

Typical energy sources include a Sparker Probe which generates vapour bubbles rich in P-waves and SH-waves (horizontally polarised shear waves), and a borehole shear-wave hammer which impacts in a up/down motion in-hole to generate SV-waves (vertically polarised S-waves). Crosshole velocities are calculated after correcting for the source-receiver distance with depth, from which bulk elastic properties are obtained.



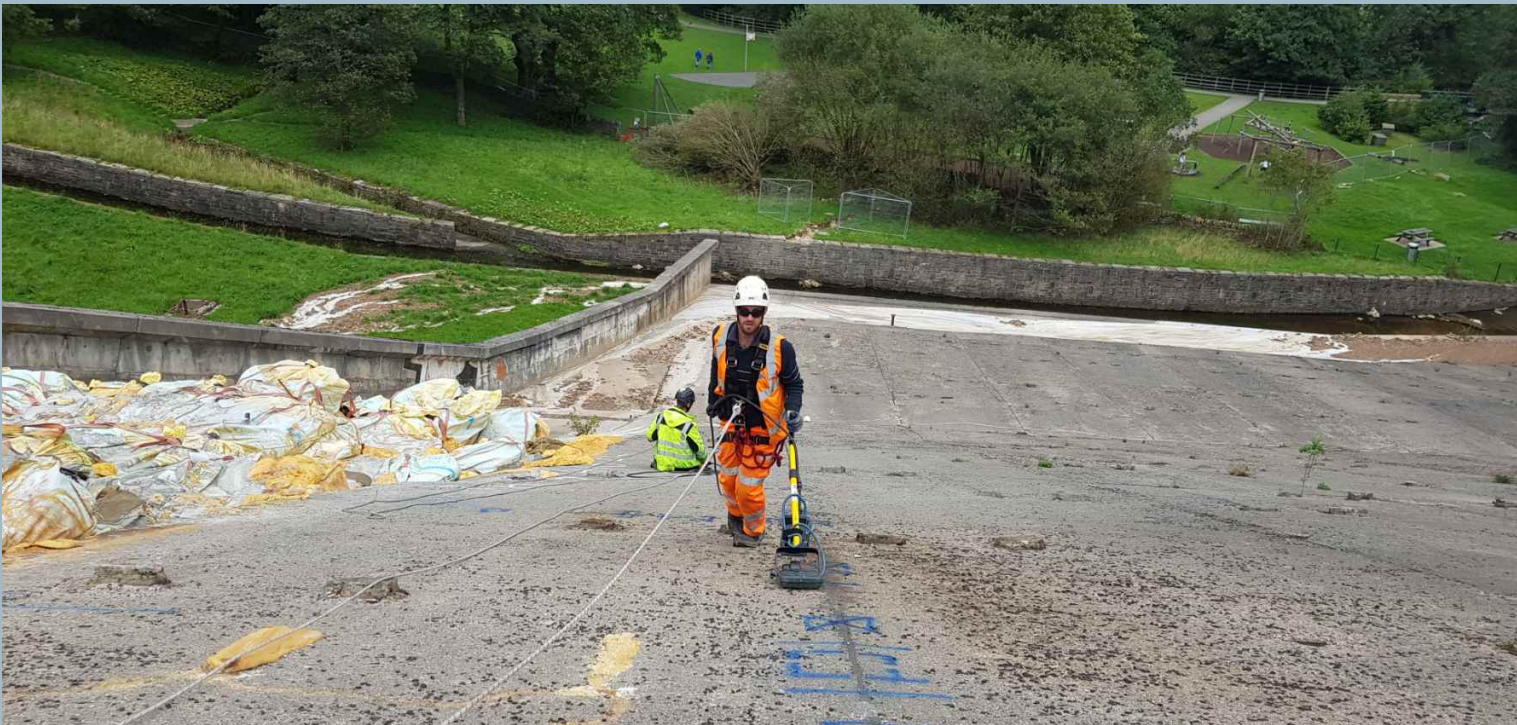
Typical crosshole seismic test set-up.



Crosshole damping GUI

In order to extract more useful information from crosshole surveys, RSK's experts have developed unique software to determine the material damping ratio with depth. By recording the response from two seismic receivers at a certain depth and using the ratio between their respective amplitude spectra, the material damping ratio can be determined for that depth.

GEOPHYSICAL APPLICATIONS



Geophysical Techniques Available

- ✓ Magnetic Gradiometry
- ✓ Ground Penetrating Radar (GPR)
- ✓ Electrical Resistivity
- ✓ Electromagnetic Mapping (EM)
- ✓ Microgravity

Applications

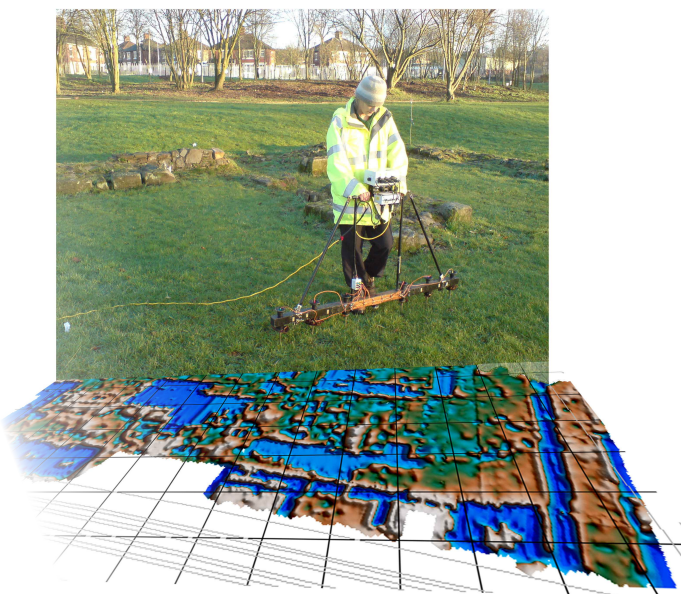
- ✓ Locating metal objects and artifacts
- ✓ Mapping historic structures (walls, foundations)
- ✓ Locating features such as ditches and pits
- ✓ Manmade voids and cavities (chambers, burials)
- ✓ Variations in soil composition/moisture

Geophysical surveys are an invaluable tool in archaeological investigation providing rapid coverage of a site where archaeological remains are believed to exist. Success relies on using staff qualified and experienced in both geophysics and archaeology. Surveys should be conducted with the appropriate methods and practices in accordance with guidance set out by the Chartered Institute for Archaeologists and Historic England. Data can aid greatly in targeting archaeological digs by supplying accurate data from which initial interpretations of archaeological remains can be made.

Survey examples

Locating Historic Ruins

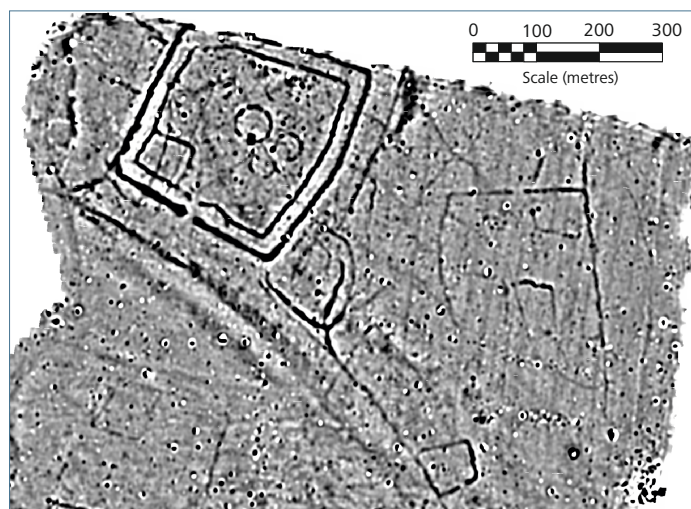
Geophysical methods rely on a physical contrast between the buried archaeological remains and the surrounding soil. In the example **above** an integrated geophysical survey comprising earth resistance (photo above) and EM (coloured map above) was conducted on the site of a medieval abbey to determine the presence of buried foundations, walls and other remains of former standing structures of archaeological interest at the site. Buried walls have a higher resistance than compared with the surrounding soils. This information was used by the client to target an archaeological dig. As a result of the geophysical investigation the time and expense of a large system of exploratory trenches was avoided.



Archaeological Evaluation

Measurements in archaeological surveys are typically collected at closely spaced intervals. In the example **right**, a rapid reconnaissance survey was conducted using a bespoke hand-held multi-sensor GPS-based magnetometer system. The survey was undertaken so that the most sensitive archaeological areas could be avoided by the development at the planning stage.

The data shows settlement activity of Iron-Age / Roman origin which includes a double-ditched square enclosure with ring-ditches and numerous discrete, linear and semi-circular anomalies. Further enclosures with settlement activity are disbursed throughout the image. The darker tones indicate an increase in the magnetic field indicating magnetically enhanced material within cut features such as a ditch. Areas of particular archaeological potential were identified for targeted follow-up surveys.



Magnetometer survey data showing numerous enclosure and ditch features. Images courtesy of Headland Archaeology (an RSK Group Company).

Locating archaeological features

Interpretation and Excavation

In the example **right** on the site of a proposed windfarm in Leicestershire, the data shows a large anomaly in the eastern field (A) which is related to a capped coal mine shaft. In the western field, the data shows numerous linear and strongly circular features indicative of human activity (B).

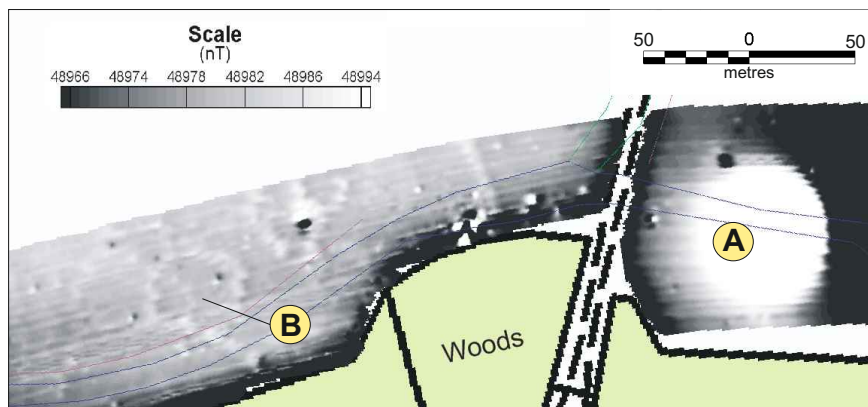
Subsequent trial trenching (marked C) across the circular feature encountered a ditch filled with animal bones and mid to late iron age pottery.

This is a good example of how excavation can be targeted to avoid 'blind trenching'. The data also shows how more recent human activity can completely mask the response from previous activities.

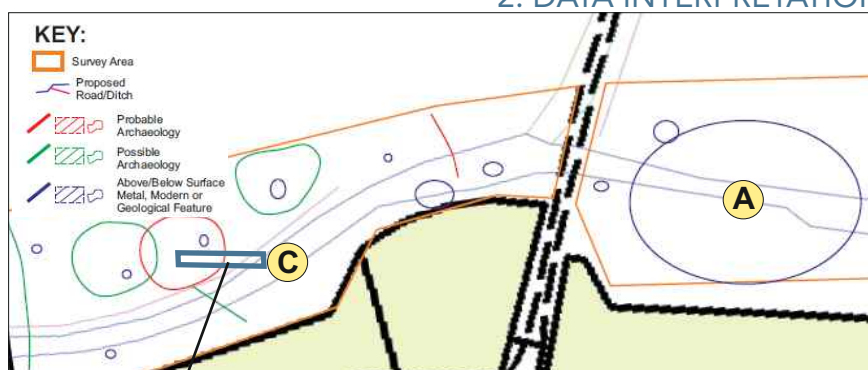


Magnetic data collection on a winters day

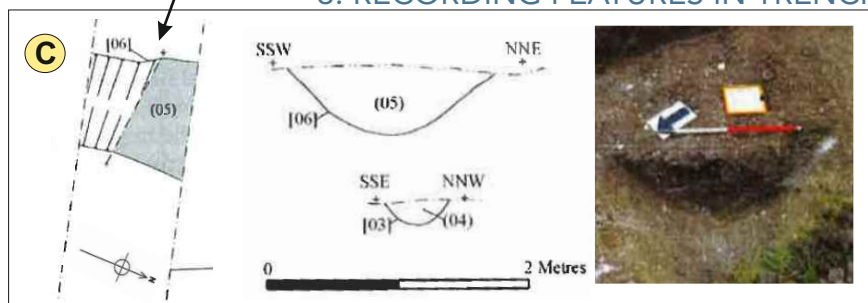
1. MAGNETIC DATA



2. DATA INTERPRETATION

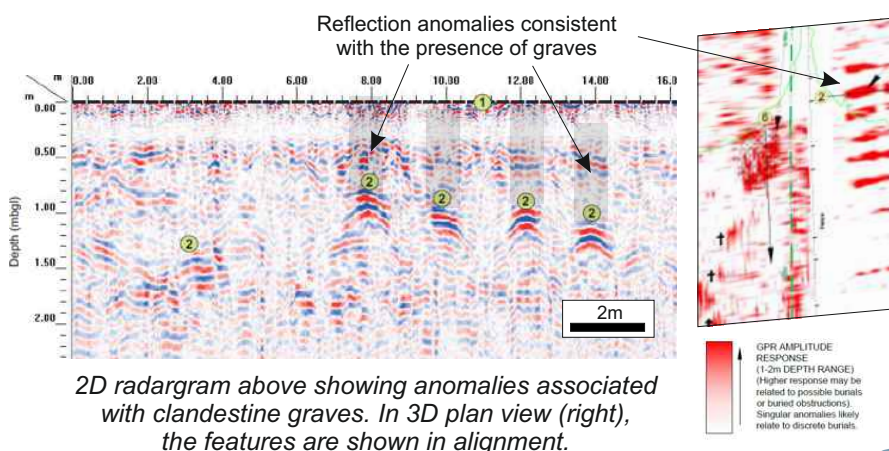


3. RECORDING FEATURES IN TRENCH



Locating Graves over a Historic Burial Ground

Geophysics can also play an important role in the detection of human remains and other buried objects, in particular clandestine unmarked graves, as part of forensic investigations. In this example, Ground Penetrating Radar (GPR) was used over a historic burial ground. The use of GPR is ideal because it is non-destructive therefore preserving the cemetery and the graves and offers a rapid means of characterising sensitive sites. As shown **below** the reflection anomalies recorded in the data are interpreted to provide extent depth and location.



Geophysical Techniques Available

- ✓ Ground Penetrating Radar (GPR)
- ✓ EM Ground Conductivity
- ✓ Electrical Resistivity Tomography
- ✓ Self Potential and Induced Polarisation
- ✓ Magnetics Surveying
- ✓ Seismic Refraction and MASW
- ✓ Microgravity

Brownfield, (or previously used) land has an important role in delivering housing and supporting UK economic growth. England is the third most densely populated county in the world and with an increasing level of new house building, the government's policy is to focus this development on brownfield land sites. These sites frequently contain poor ground conditions, contamination issues and a plethora of unknown underground obstacles associated with previous land use which may cause costly engineering and environmental issues and delays to the developer if they remain undetected.

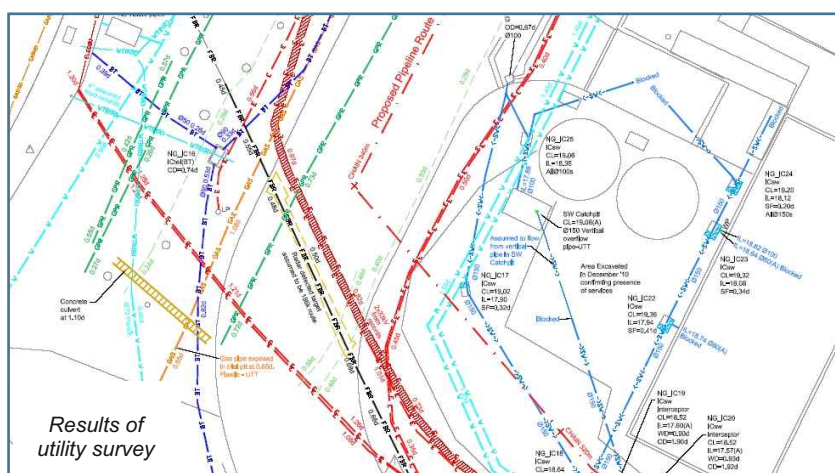
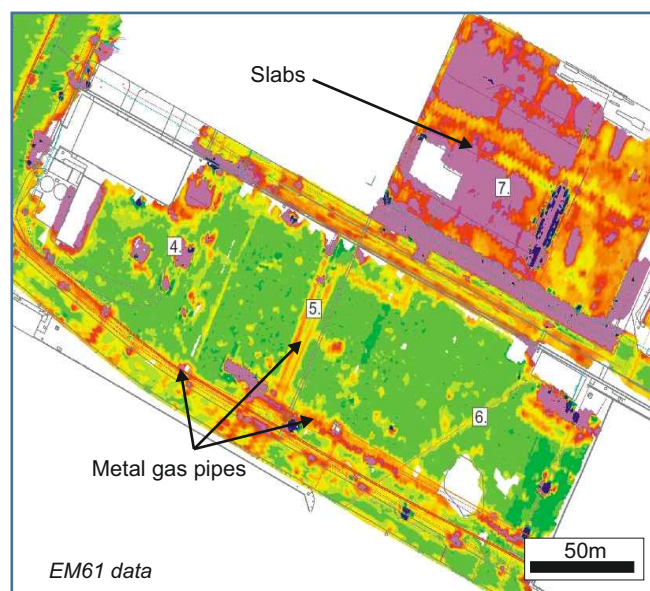
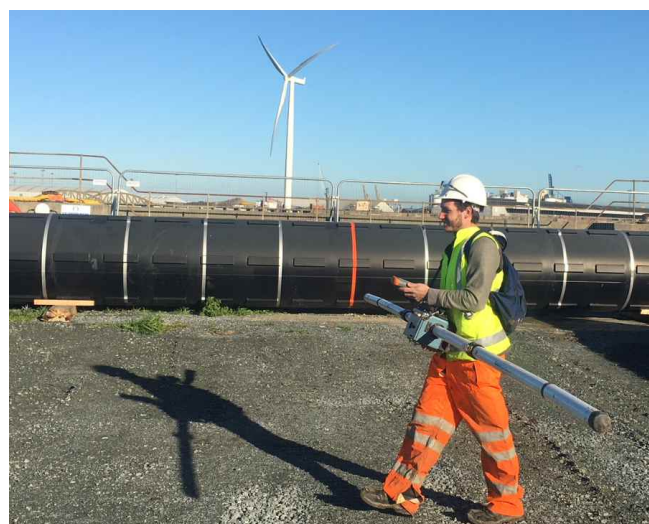
Geophysical techniques can play an important role in reducing costs and risks by providing rapid site reconnaissance surveys to characterise subsurface features prior to any intrusive investigation. Rapid data collection rates (typically 2 Ha or more per day), and specialist data processing techniques, mean that preliminary results can usually be offered soon after the completion of a survey, providing an invaluable tool in the reduction of risk from unforeseen ground conditions.

Data Examples

The data **right** was recorded over a former industrial site that was proposed for a new power station. As part of a gas pipeline route investigation, a multi-disciplinary geophysics investigation was carried out to determine the presence and location of all below ground services, foundations, geological constraints and other obstructions that would render it infeasible to lay a large diameter steel gas pipe. The resulting GPR and electromagnetic surveys clearly identified which structures remained in-situ and which had been removed. The resultant utilities drawing showing all the hazards crossing the proposed route provided invaluable information, with the final phase of verification of the geophysical results by trial trenching.

Applications

- ✓ Locating buried obstructions
- ✓ Mapping underground structures
- ✓ Locating buried drums and tanks
- ✓ Mapping extent of contamination
- ✓ Detecting changes in the groundwater

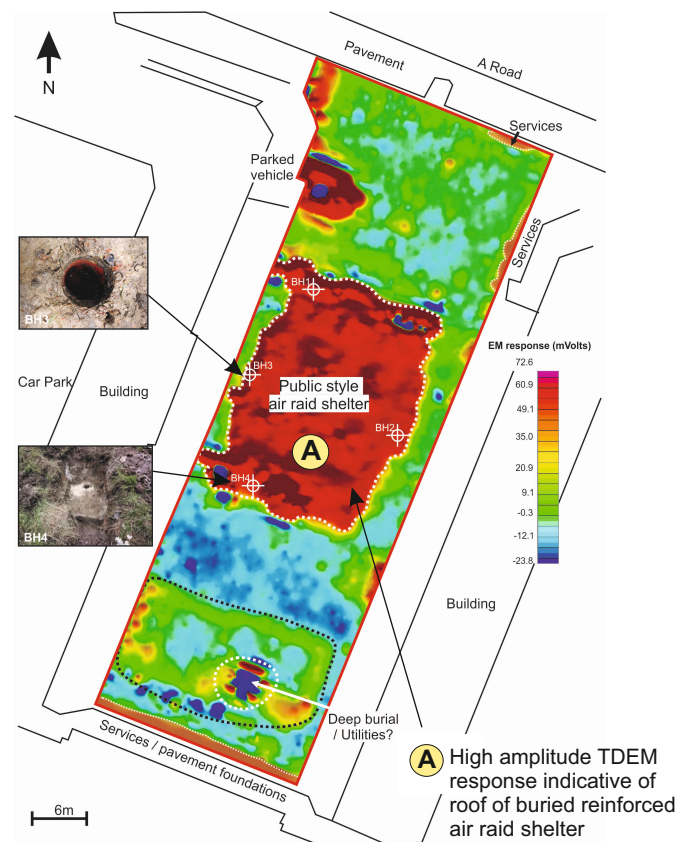


Former Land Use Determination

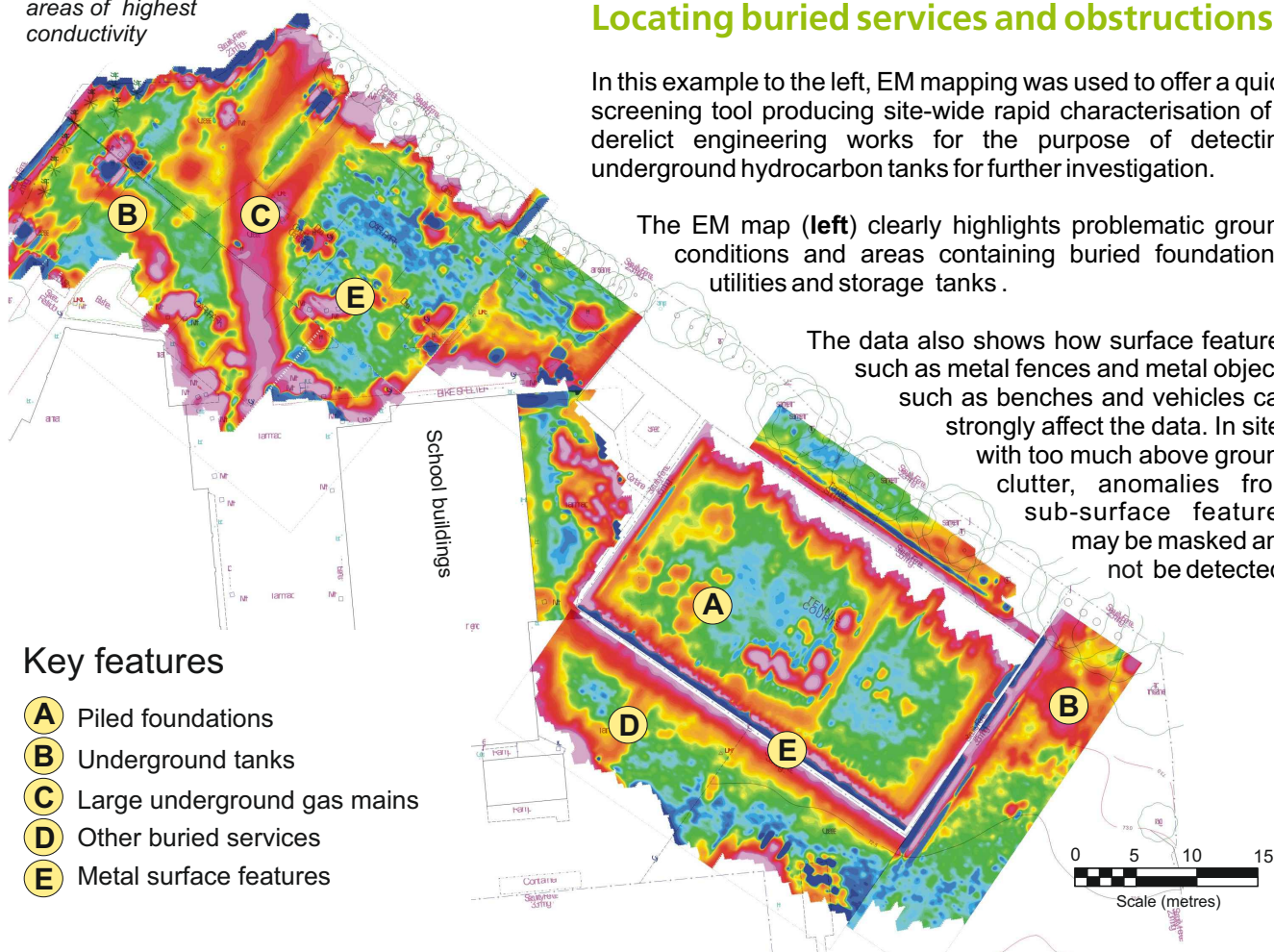
As part of geoenvironmental site investigations, determining the former land use of a site can provide a useful base for determining the likely sources and locations of contamination and/or obstructions prior to re-development. Historical maps and other desk study data are a vital source on information, but do not reveal whether the structures are still present, and can be ambiguous. The example below show how geophysics can be used as part of a phased approach to SI.

Locating buried air raid shelters

In this example to the **right**, the site comprises an area of landscaped ground between two residential buildings. Historic plans showed the presence of a buried air raid shelter at the site. A TDEM survey was conducted across the area to highlight areas of high response associated with buried man-made in-situ structures. In this instance a geometric shaped very high response is observed showing the location of the roof of the buried reinforced air raid shelter. Based on the results of the survey, intrusive coring was targeted on each edge of the structure to confirm its size, thickness of concrete and presence of voids within.



Reds and pinks show areas of highest conductivity



Locating buried services and obstructions

In this example to the left, EM mapping was used to offer a quick screening tool producing site-wide rapid characterisation of a derelict engineering works for the purpose of detecting underground hydrocarbon tanks for further investigation.

The EM map (**left**) clearly highlights problematic ground conditions and areas containing buried foundations, utilities and storage tanks.

The data also shows how surface features such as metal fences and metal objects such as benches and vehicles can strongly affect the data. In sites with too much above ground clutter, anomalies from sub-surface features may be masked and not be detected.

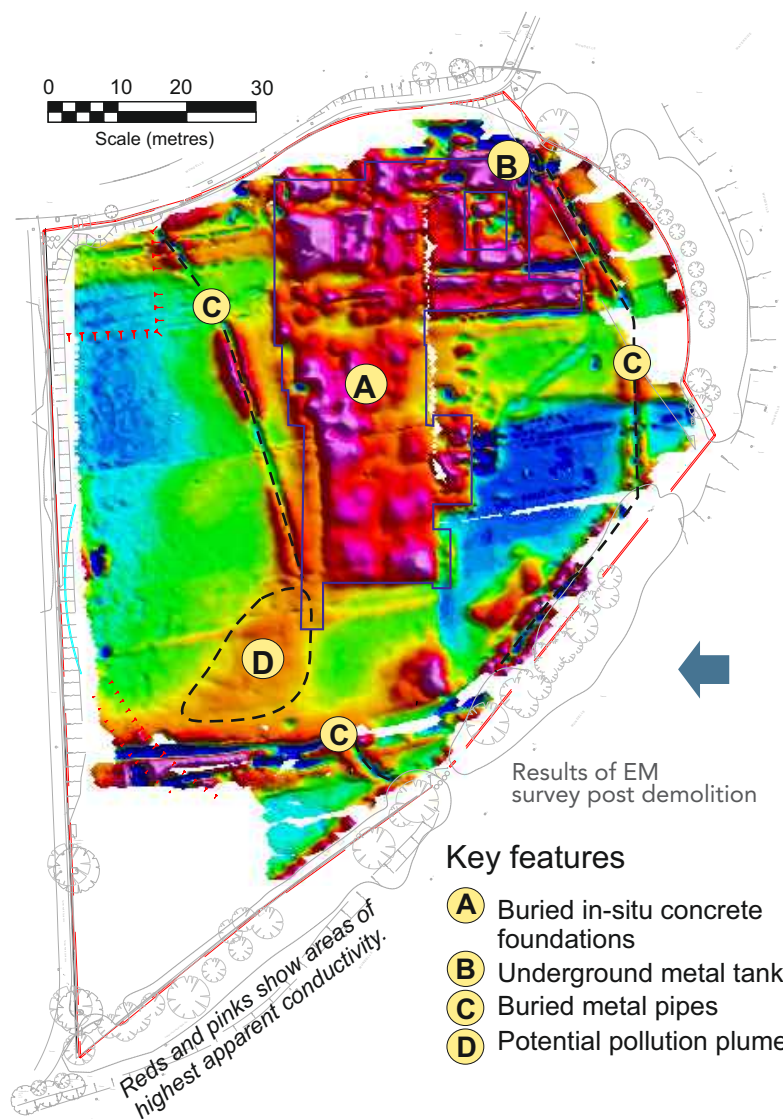
Site characterisation

Site characterisation is the first and most important step in brownfield site and contaminated land investigation. Features missed by conventional site investigation techniques can be identified in the initial stages by geophysics. A comprehensive understanding of the ground conditions and contamination issues at a site is vital to the process of producing an accurate and cost-effective remedial strategy. Where risk assessment requires total site coverage to trace all possible sources and pathways of contamination the use of geophysics should be considered.

Geophysical techniques can image and detect variations in the ground based on physical and chemical properties without breaking through the ground surface. These can be used to identify obstructions, underground structures, locate buried drums and tanks, determine extent of contamination and detect changes in the groundwater.

In this example **below**, EM ground conductivity was used to offer a quick screening tool producing site-wide rapid characterisation of a site which had been demolished entirely to ground level. All structures below ground were understood to have been removed, but the EM data clearly showed otherwise.

The results clearly highlight potential sources of contamination such as tanks and utilities, subsurface pathways like buried foundations of former structures and also an area of possible contamination where a broken pipe had leaked to the surrounding ground. This information was used to inform the subsequent intrusive investigation and dictate the best location for targeted trial pits and boreholes.



Site before demolition



Site after demolition

Mapping contamination

Mapping variations in the electrical conductivity of the subsurface across a site can highlight anomalously conductive targets such as metallic tanks, pipework and also any ground contamination. Although water is generally not a good conductor of electricity, groundwater - especially contaminated groundwater - contains dissolved compounds and ions that may greatly enhance its ability to conduct electricity.

Contaminated Land Investigations

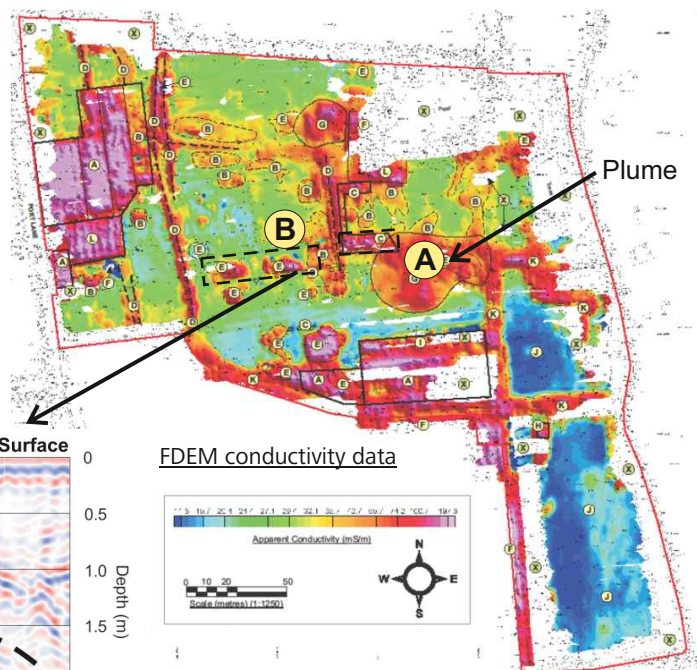
As a legacy of the world's first industrialised country, the UK has over 400,000Ha of contaminated land today. As part of the Part 2A regime, all potentially contaminated sites in the UK need to be investigated.

The use of geophysical techniques is an invaluable tool in the investigation of contaminated sites and can be used as rapid site reconnaissance tool without the exposure of site personnel to the hazards of contaminated sites.

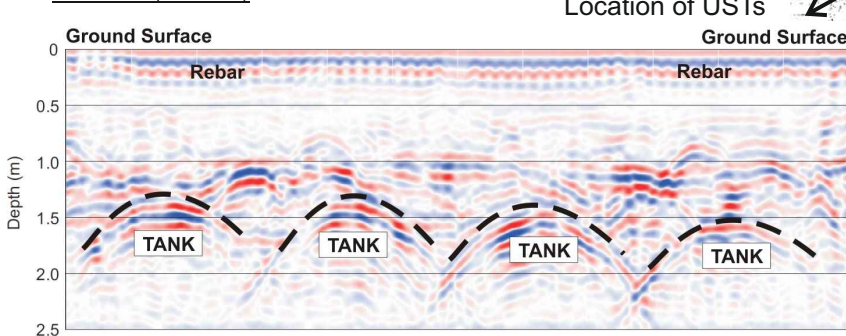
As described in guidance from CL:AIRE, geophysical techniques can form an integral part of the site investigation of contaminated ground at all stages, from the preliminary Phase 1 investigation to highlight areas of potential contamination in order to target conventional intrusive methods; to the main Phase 2 investigation to augment and confirm borehole information to improve the Conceptual Site Model; through to the latter phases such as the monitoring and validation of remedial measures.

Detecting old buried tanks and petrol contamination

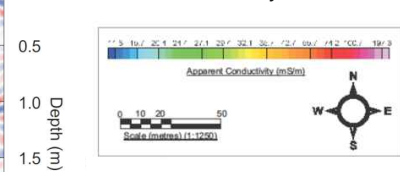
In the example **right**, the EM data show an area of elevated conductive ground adjacent to a number of tanks at a former engine works. LNAPL plumes can become more conductive with age due to biodegradation. A subsequent intrusive ground investigation of the site revealed the presence of increased levels of hydrocarbon contamination.



GPR Data (400Mhz)



FDEM conductivity data

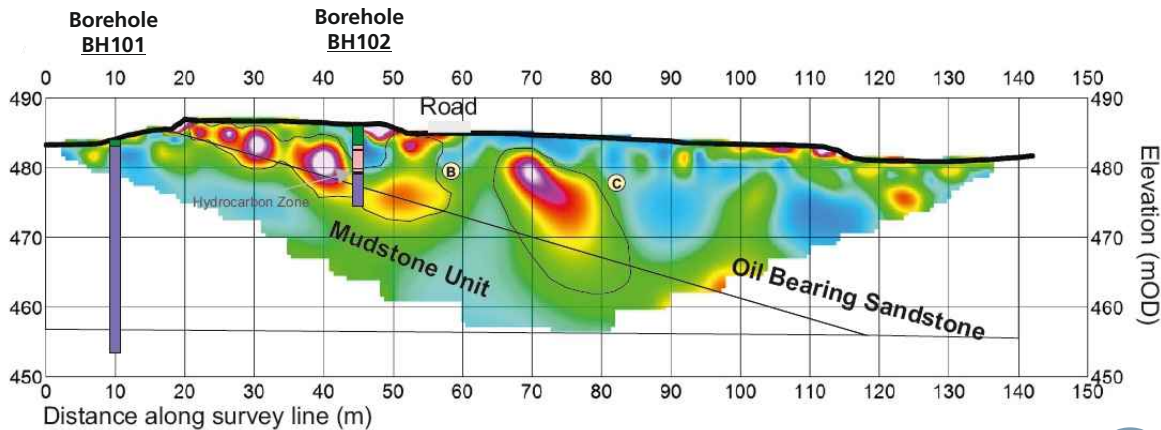


Broad hyperbolic reflectors in the radar data confirm the presence of USTs

Locating heavy hydrocarbon contamination

In this example **below**, RSK was appointed to help with the delineation of a spillage of crude oil from a tanker loading station. Hydrocarbons are excellent insulators – as a result have very high values of resistivity. For this reason, we can use the resistivity technique to locate Hydrocarbon contamination in the ground.

The resistivity data shows the existence of dipping high resistivity anomalies – coloured reds and purple – that shows where the heavy DNAPL oil is present within fractures in the sandstone bedrock, constrained by marl below. This information helped to identify where to concentrate subsequent investigations and remedial works.



Geophysical Techniques Available

- ✓ Electrical Resistivity
- ✓ Electromagnetic Mapping (EM)
- ✓ Ground Penetrating Radar (GPR)
- ✓ Magnetic Gradiometry
- ✓ Seismic Refraction

Historically, disposal to Landfill was the conventional method of waste disposal in the UK. As a result of this legacy, the UK has around 20,000 operational and closed landfill sites, many of which are not engineered and are unprotected to the environment. Even new landfill sites based on the principle of engineered containment are at risk of leachate leaking through the base and sides to cause contamination of surrounding land and groundwater pollution, with potentially serious consequences to drinking water resources.

Applications

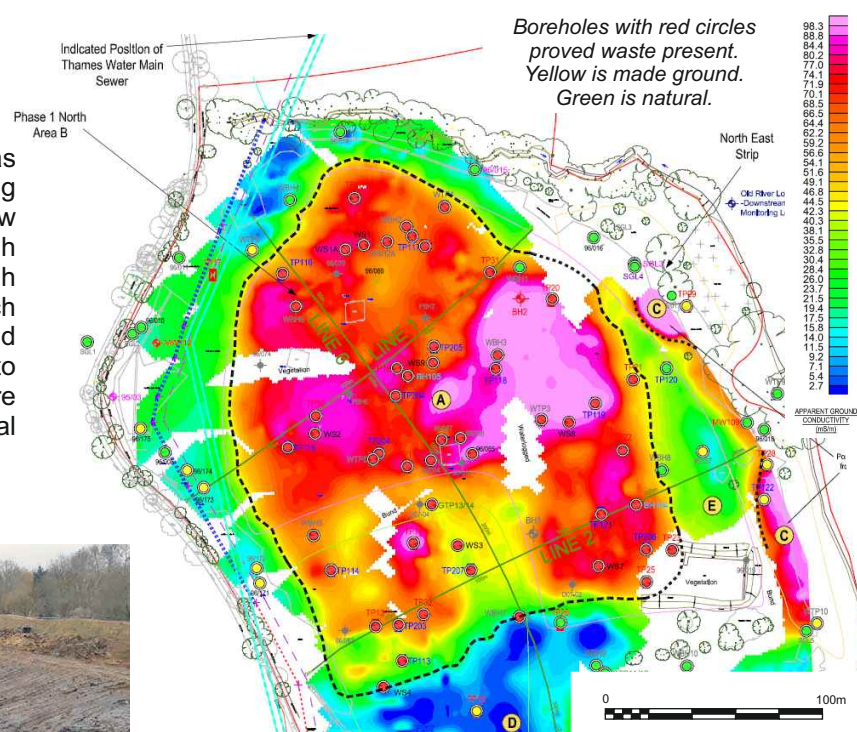
- ✓ Locating landfill boundaries
- ✓ Mapping variations in waste composition
- ✓ Mapping leachate plumes
- ✓ Locating buried infrastructure
- ✓ Locating voids and areas of poor compaction

Geophysical surveys are often the only practical method of investigation on landfills as they do not involve penetration of the cap or liner and exposure of any hazardous wastes. Geophysics can be used in a wide range of landfill applications from determining the location and geometry of old landfills, through to aiding the investigation of groundwater pollution and migration pathways in the subsurface, essential for demonstrating compliance with IPPC requirements.

Survey examples

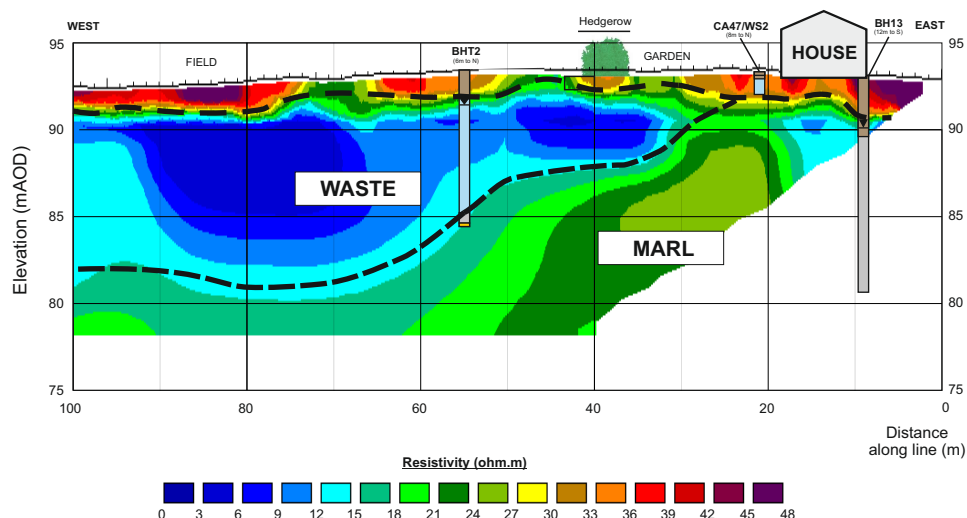
Defining Landfill Boundaries

In this example to the **right**, an EM31 survey was carried out across a closed landfill site containing industrial waste. The high values (reds) show the lateral extents of the waste. The high conductivity values are an indication of high saturation levels and leachate content which contain significant amounts of dissolved ions and organic acids. The boundary locations fed into critical calculations of waste volume which here has been used to accurately estimate the total material amounts for remediation.



Defining Landfill Depth

In addition to the lateral extent, the thickness of waste is often an important unknown. In the example to the **right**, resistivity imaging was used across residential gardens into a field on the west containing a former landfill. The low resistivity waste mass is shown coloured blue in the resistivity cross section. Borehole data confirmed this interpretation. The detailed ground model developed by the integrated site investigation allowed effective gas protection measures to be designed.



Defining Landfill Boundaries with Integrated Data Sets

By integrating data sets from different techniques a more accurate determination of landfill characteristics can be achieved than from a single technique alone:

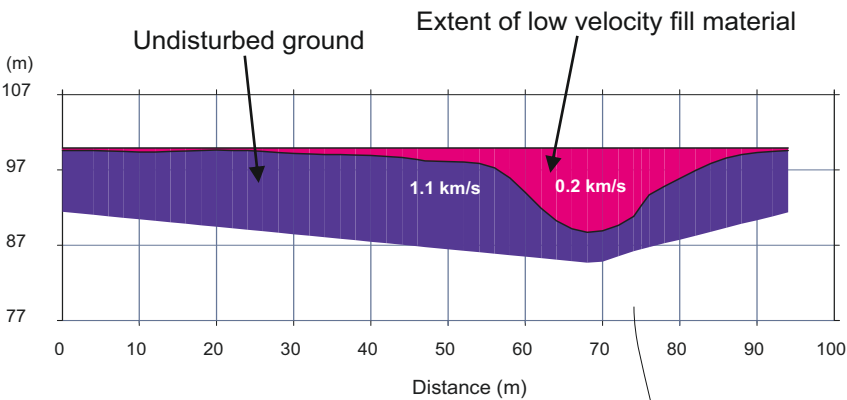
- A** Seismic refraction identifies the boundary between the waste and bedrock.
- B** Surface mapping of subsurface conductivity defines the landfill periphery.
- C** Electrical resistivity imaging provides a cross section of the landfill defining the vertical extent of the waste and it can also identify any leachate beneath the landfill liner and in the surrounding ground.

For more information scan QR-Code: [‘Mapping Britain’s Hidden Landfills using Integrated Geophysical Methods: A Case Study’, FastTIMES Special Issue: Environmental Geophysics, 22/1 \(2017\)](#)

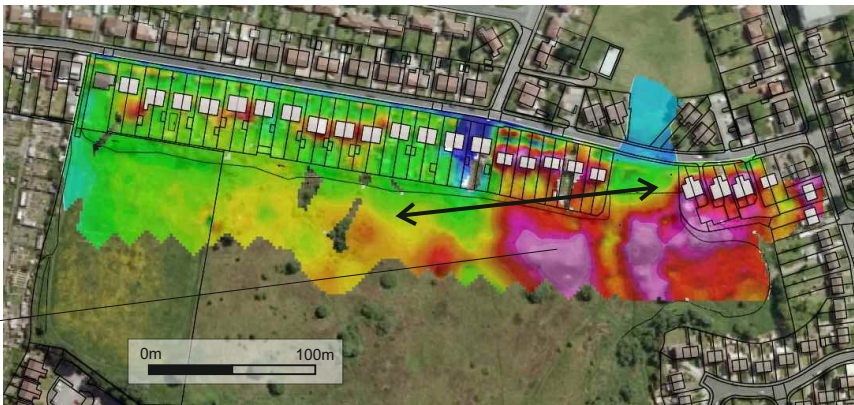


This shows an area of high conductivity (coloured red/pink) delineating the lateral extent of the main waste mass

A Seismic refraction results



B EM Conductivity Data



C Electrical resistivity cross sections in 3D



Geophysical Techniques Available

- ✓ Electrical Resistivity
- ✓ Electromagnetic Mapping (EM)
- ✓ Ground Penetrating Radar (GPR)
- ✓ Magnetometry
- ✓ Microgravity
- ✓ Seismic Refraction and MASW

Some of the earliest applications of geophysics were to determine the geological structure of the subsurface. Changes in subsurface lithology often represent variations in physical properties. These variations can be detected by geophysical methods and interpreted in terms of the geological ground model.

Survey examples

Fault Mapping

Geophysical surveying across a site can highlight variations in sediment thickness and bedrock depth. It is especially useful for filling the information gap between boreholes.

To the **right** is a seismic refraction line identifying the location of a fault in the bedrock. The high velocity competent bedrock (red) is shown to step down by 10m. The thickness of the low velocity less competent unconsolidated deposits is shown coloured green.

In the example to the **right** resistivity tomography was used on a site in Bristol to map the ground along a new bus transit route. The interface between the high resistivity sandstone bedrock to the left and low resistivity mudstone is marked by a large fault. Also shown in the data is 10m of waste in landfill site in the top right of the section.

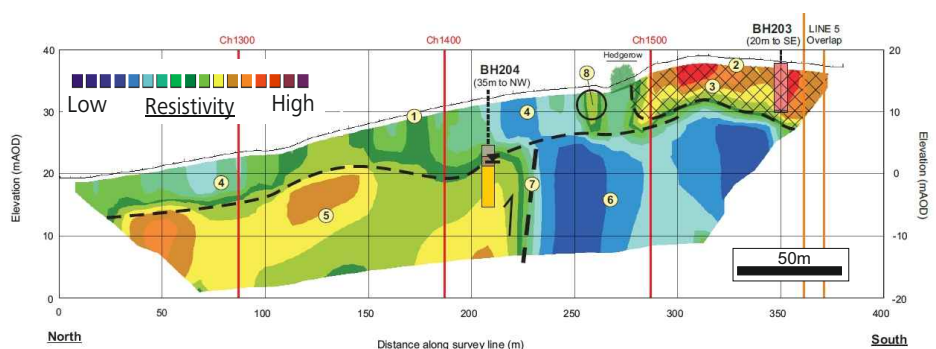
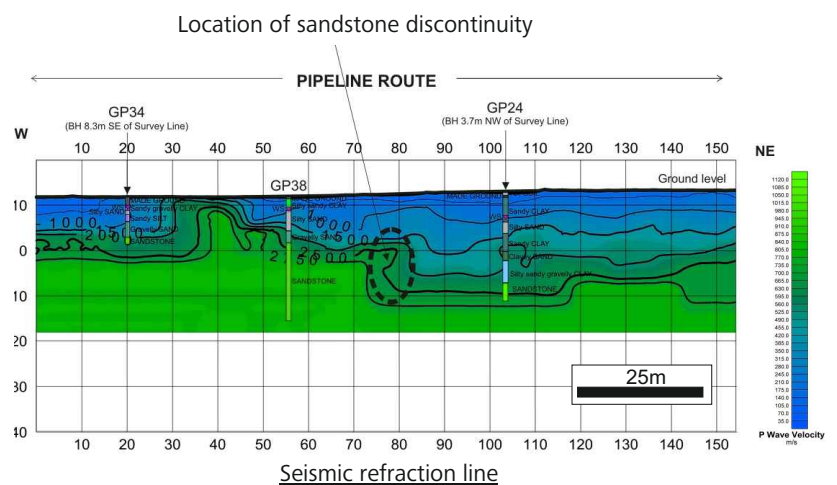
Imaging shallow stratigraphy and former river channel channels with GPR

At this site, low frequency (200MHz) GPR was used to determine the location of former gravel filled river channel deposits. A man-made mill chase had diverted the current river from its former natural course. The current river was running dry and as a chalk stream of global significance, a restoration project was being undertaken to recreate the river to its old river channel. The GPR survey was highly successful in detecting the saturated gravel deposits as high amplitude lenses. This is shown **right** in 2D profile. The former braided channel is clearly seen in 3D depth plots.

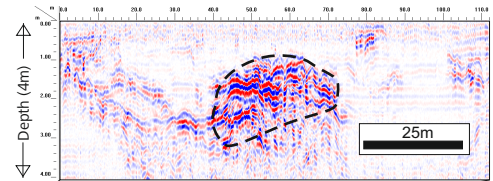
Applications

- ✓ Thickness of Soils
- ✓ Thickness of superficial deposits
- ✓ Depth to bedrock
- ✓ Depth to groundwater table
- ✓ Fault mapping
- ✓ Locating and characterising mineral despoits

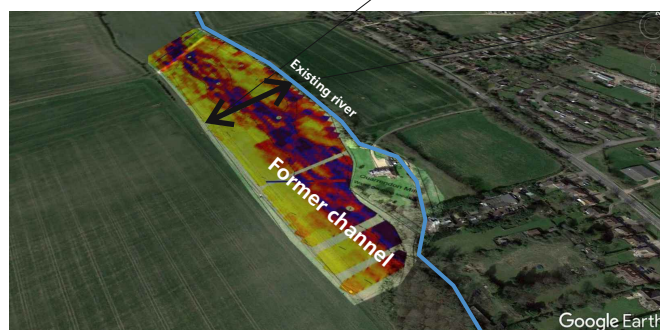
In situations where the geology or depth to bedrock is poorly understood, geophysics can provide valuable information. Natural voids, sedimentary structures, or fractures and faults can cause significant engineering problems if they remain undetected.



2D GPR Profile:



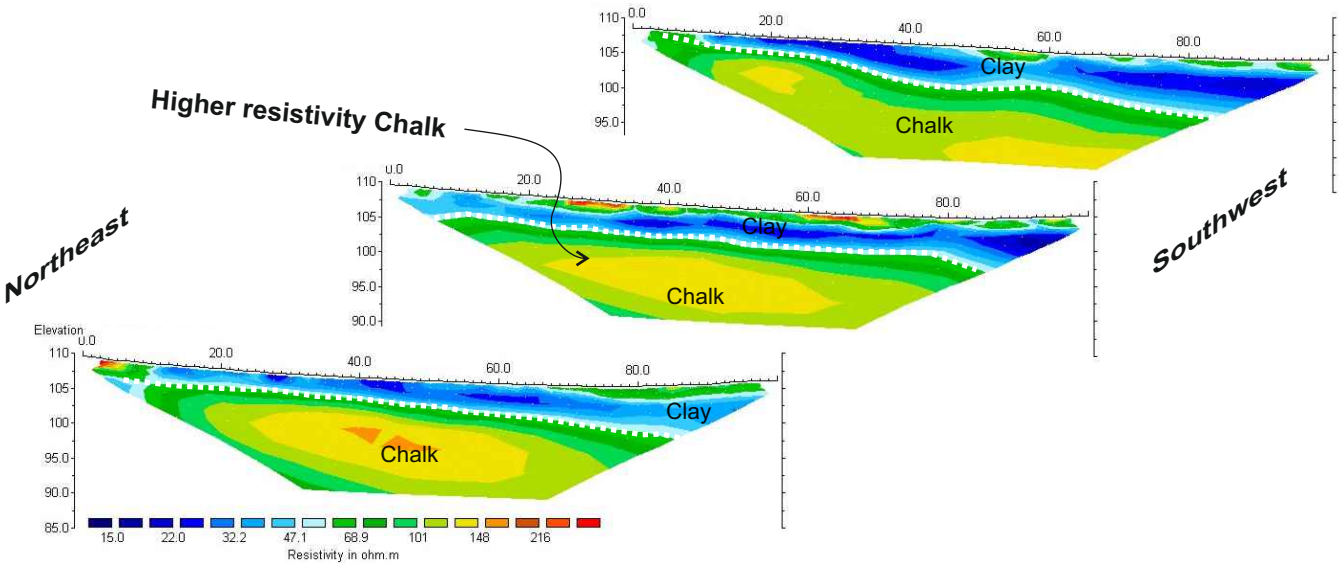
3D GPR Amplitude Plot at 2.0 m depth:



Mapping Depth to Bedrock with Resistivity Imaging

In the example **below**, a series of electrical resistivity imaging surveys were conducted across a 4Ha site proposed for a housing development. Combined with data from a small number of targeted window sampler

holes, the survey successfully defined the depth to the Chalk and the nature of the geological contact accurately across the entire site. The geophysical survey was able to be completed in just two days.

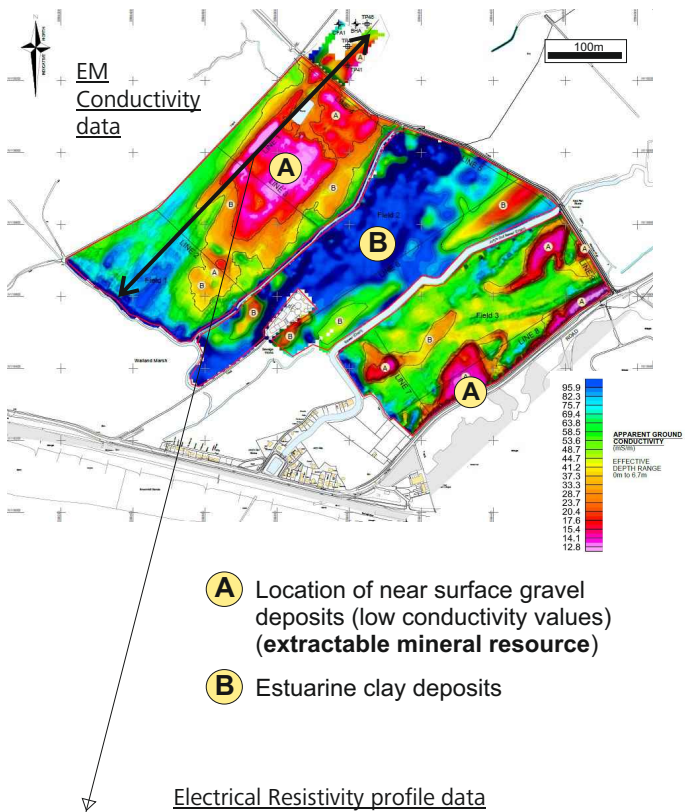


Characterising Mineral Deposits using Integrated Geophysical Techniques

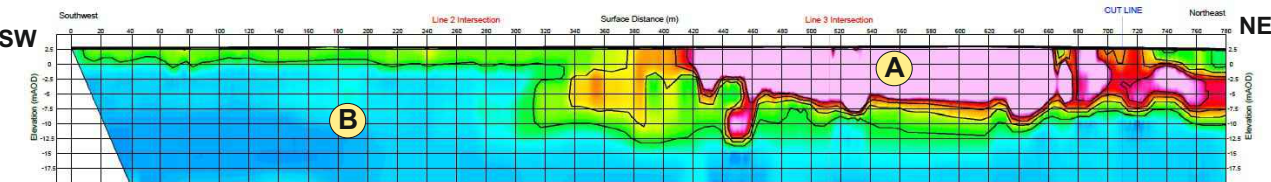
The extraction of sand and gravel deposits is essential to the continued smooth functioning of the countries construction industry. Aggregates are the most commonly used construction minerals in the UK. Nationally, sand and gravel is used for concrete, roadstone, asphalt and many other applications used in the construction of buildings and infrastructure. Geophysical surveys can play a vital role in the identification of high quality gravel deposits, including providing information of whether the resource is likely to be economic to extract such as the lateral extent and thickness of mineral, and amount of overburden.

In this example, EM ground conductivity was conducted across a large (75Ha) open site to show the extent of gravel deposits on a shingle spit. The gravel material is low in conductivity values (see image **right**) compared to the surrounding underlying clays. This allowed the area of the gravels deposits to be determined.

An electrical resistivity survey was also carried out in a grid of lines across the site. This clearly showed the thickness of the gravel deposits (see **below**). The combination of both geophysical datasets allowed for the volume and mass of the potential gravel resource to be calculated to enable the successful planning and design of a new quarry.



- A** Location of near surface gravel deposits (low conductivity values) (extractable mineral resource)
- B** Estuarine clay deposits



Geophysical Techniques Available

- ✓ Microgravity
- ✓ Ground Penetrating Radar (GPR)
- ✓ Electromagnetic Mapping (EM)
- ✓ Electrical Resistivity Tomography (ERT)
- ✓ Multi-channel Analysis of Surface Waves (MASW)

Subsurface voids (whether naturally occurring or manmade) and associated areas of soft ground present a significant risk to future, and existing, infrastructure and buildings. Unknown voids can be discovered during construction and can cause hazards and expensive delays to a construction project. Manmade cavities, including mine workings, and shafts are just as hazardous and can be even more common than natural features.

Survey examples

Ground Penetrating Radar (GPR)

A number of unforeseen circular anomalies were uncovered during soil stripping works at a new residential development on a greenfield site in the East of England. Further desk study information revealed that the site may be at risk of solution features due to the shallow nature of chalk bedrock present.

A trial GPR survey was undertaken to identify the location of any anomalies associated with the solution features at the ground surface. The GPR data showed a number of discrete areas exhibiting high amplitude anomalies and disturbed ground indicative of the presence of voided and loosely filled ground. Dynamic probes subsequently targeted on the GPR anomalies (see **right**) confirmed the presence of very loose infill material and voided areas. Based on the results, the GPR survey was extended to cover the full site.

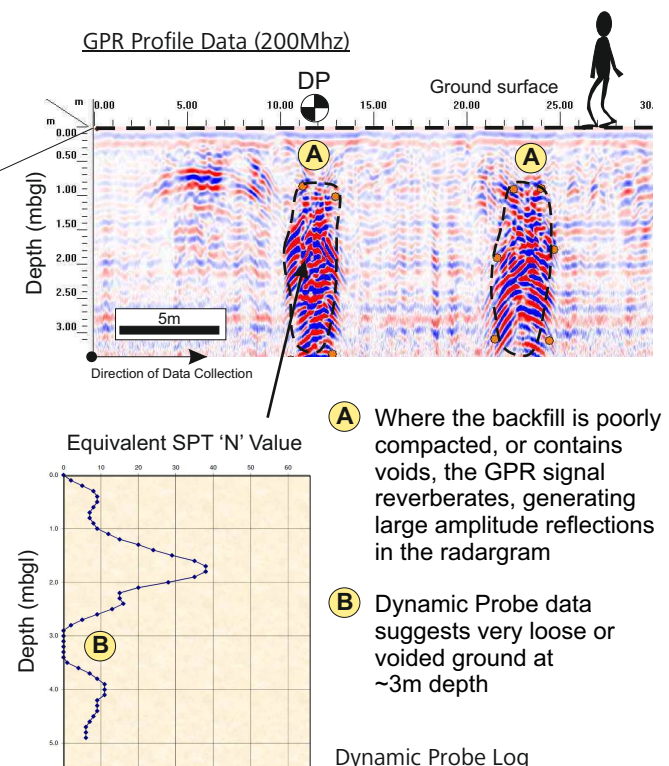
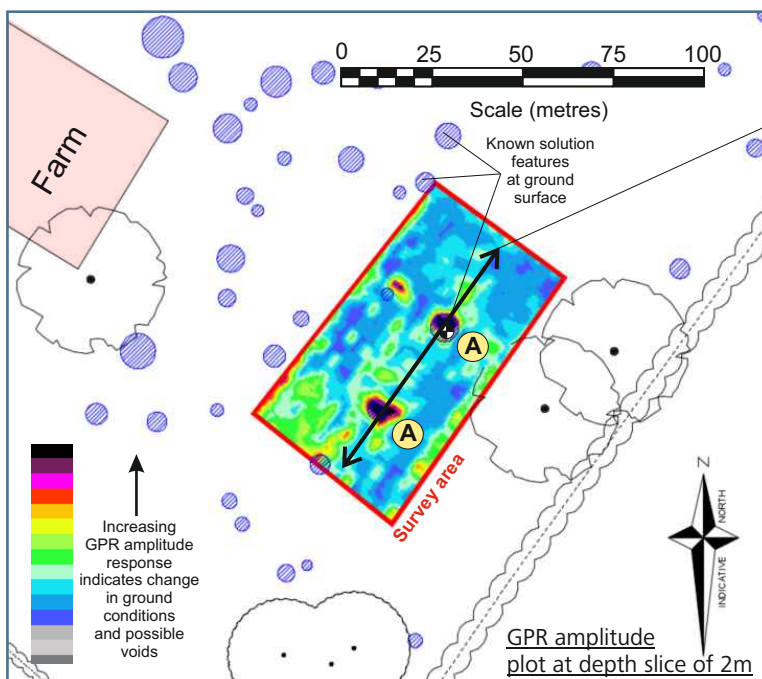
Applications

- ✓ Locating natural cavities (caves, fissures and solution features)
- ✓ Locating man-made cavities (mineworkings, shafts, adits)
- ✓ Locating hidden tunnels and basements

Geophysical techniques provide a suite of site reconnaissance tools that enable site characterisation and provide total site coverage. The examples below illustrate how relatively simple geophysical surveys can be applied to a site in order to plan and design a targeted intrusive investigation and subsequent remedial works to problem areas of ground. The use of geophysics reduces the associated risks and saves the developer time and money during the project.



Acquisition of low frequency GPR data



VOIDS AND SOFT GROUND

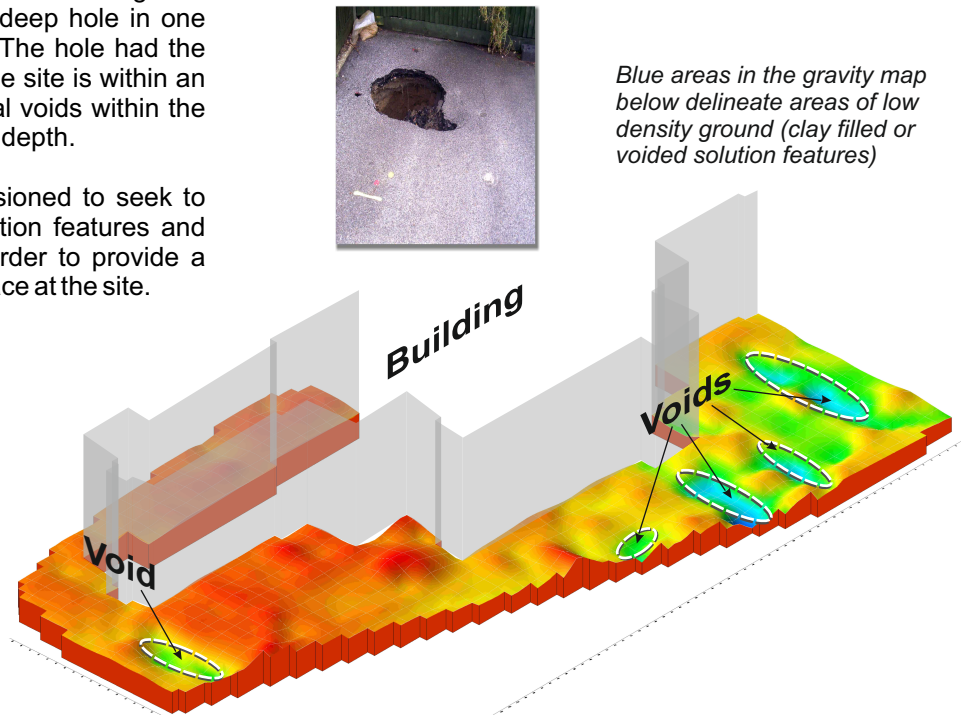
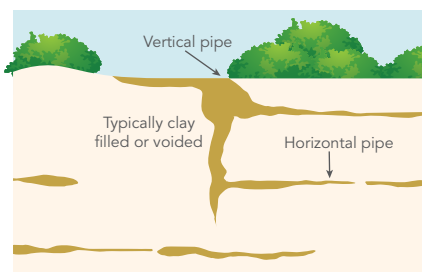
Microgravity Mapping

Microgravity involves the detection of the variation in sub-surface density, such as those produced by voids and cavities. The examples below highlight the use of microgravity in the detection of solution features and historic chalk mineworkings.

In the first case, the trigger event for the investigation was the formation of a small 1.3m deep hole in one corner of a site (see photo **right**). The hole had the characteristics of a small doline. The site is within an area known to be affected by natural voids within the chalk bedrock, which lies at about 7m depth.

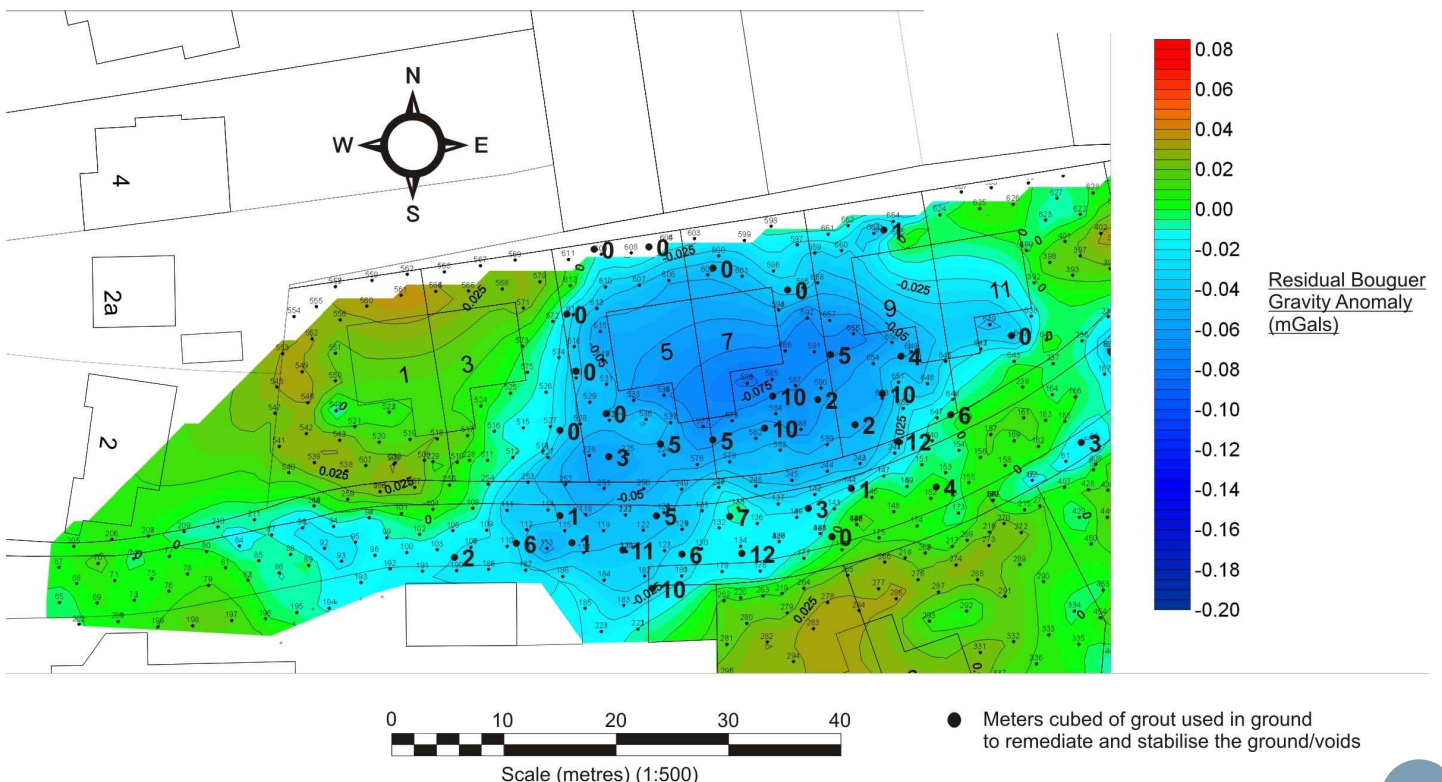
A microgravity survey was commissioned to seek to determine the lateral extent of solution features and voids within the chalk bedrock in order to provide a reliable interpretation of the sub-surface at the site.

The results of the microgravity survey (**below**) show a number of areas of low density ground. A subsequent intrusive survey comprising dynamic probing confirmed very weak or voided ground at these locations therefore successfully pinpointing all the problem areas needed for remedial works.



Blue areas in the gravity map below delineate areas of low density ground (clay filled or voided solution features)

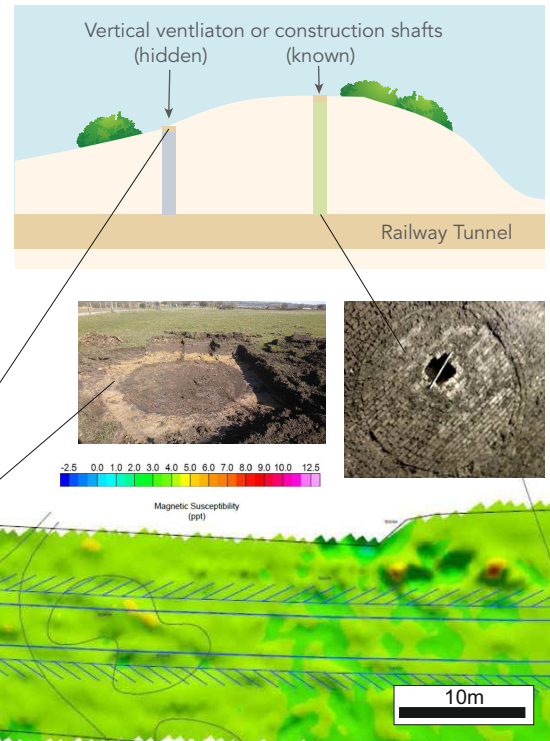
In the example **below**, a gravity survey was carried out on a residential street. The ground comprises made ground over chalk. A microgravity survey was commissioned when subsidence features occurred on the surface. Grouting was subsequently targeted over the gravity low and hundreds of cubic meters of grout were injected in the ground to stabilise it. Targeting the grouting using the geophysics ensured that the risks of any further collapse were minimised.



Mineworkings and Shafts

EM Conductivity

Historic mineworkings are present below approximately 3 million properties in the UK. Unstable, shallow, abandoned workings pose the largest threat to overlying developments and land. Hidden unrecorded shafts can therefore pose significant cost to developers if encountered on site. In the example **below**, an electromagnetic conductivity survey was undertaken on a land overlying a railway tunnel with suspected hidden shafts. The EM data clearly shows a large circular anomaly associated with a reinforced cap / support structure. The presence of the shaft (not known about previously) was subsequently ground truthed with a targeted trial pit.

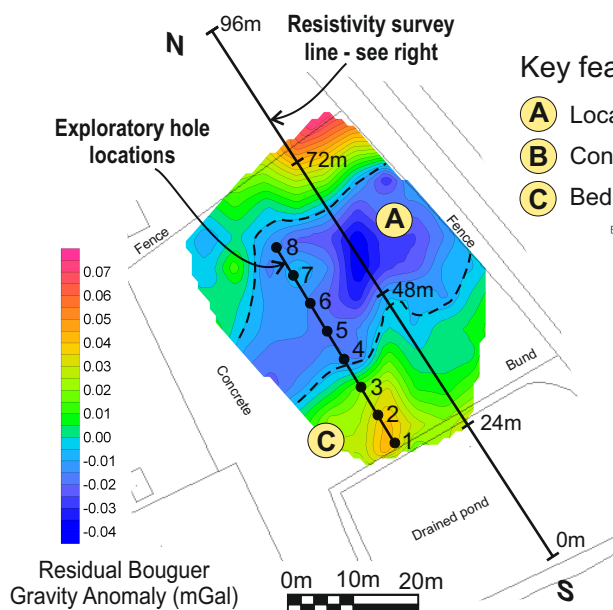


Tunnel alignment

EM conductivity (in-phase) data collected along the tunnel alignment on the surface above showing large response from a reinforced capping structure above a railway tunnel shaft

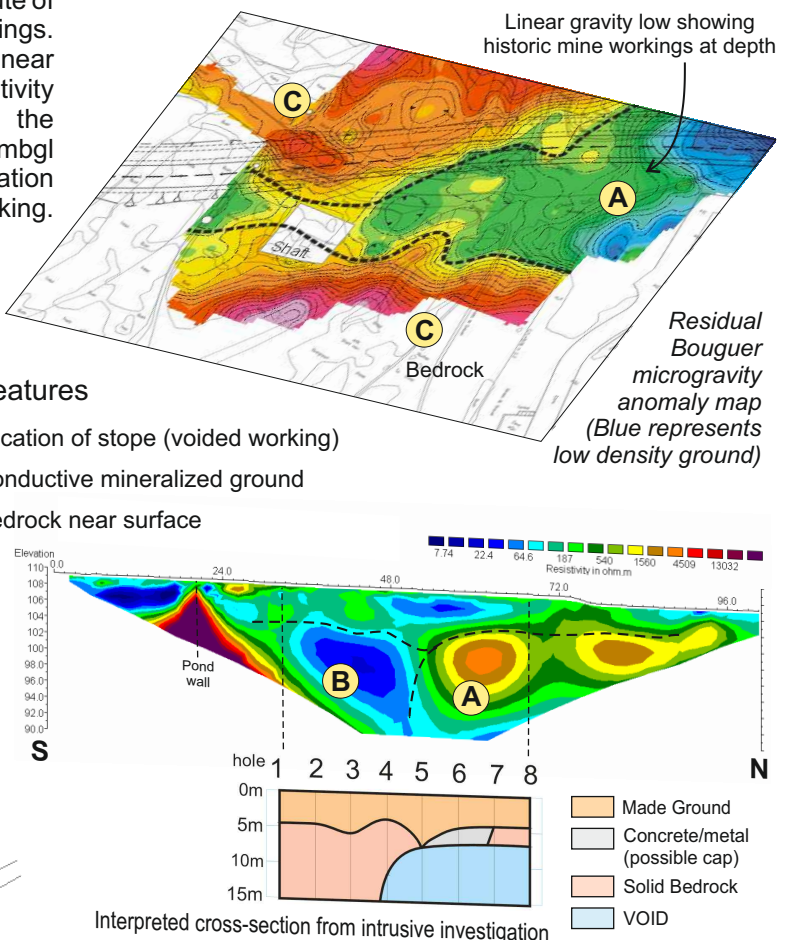
Locating Mineworkings using Integrated Geophysical Techniques

A microgravity survey was conducted over the route of a proposed road to locate former tin mine workings. The gravity data (**below left**) clearly shows a linear anomaly indicating low density ground. A resistivity survey (**below right**) was carried out across the anomaly and shows an area of high resistivity at 6mbgl indicative of a void. A follow up intrusive investigation confirmed the presence of the voided mine working. Further gravity surveys (**right**) revealed the presence of additional mine workings across the site.



Key features

- (A) Location of stope (voided working)
- (B) Conductive mineralized ground
- (C) Bedrock near surface



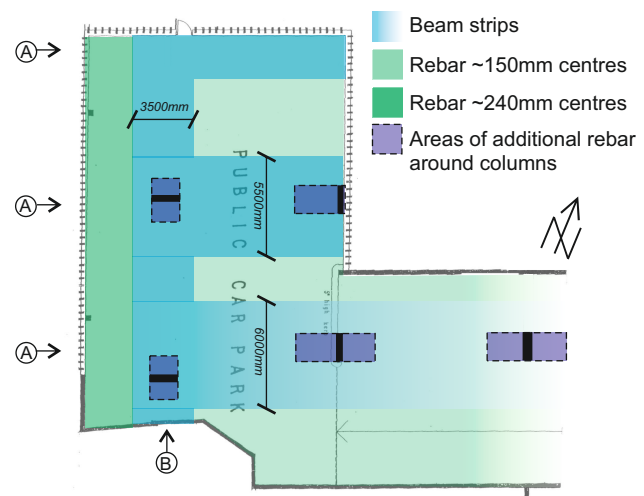
Structural Investigations using Ground Penetrating Radar (GPR)

The GPR technique has proved to be powerful and versatile in structural investigations.

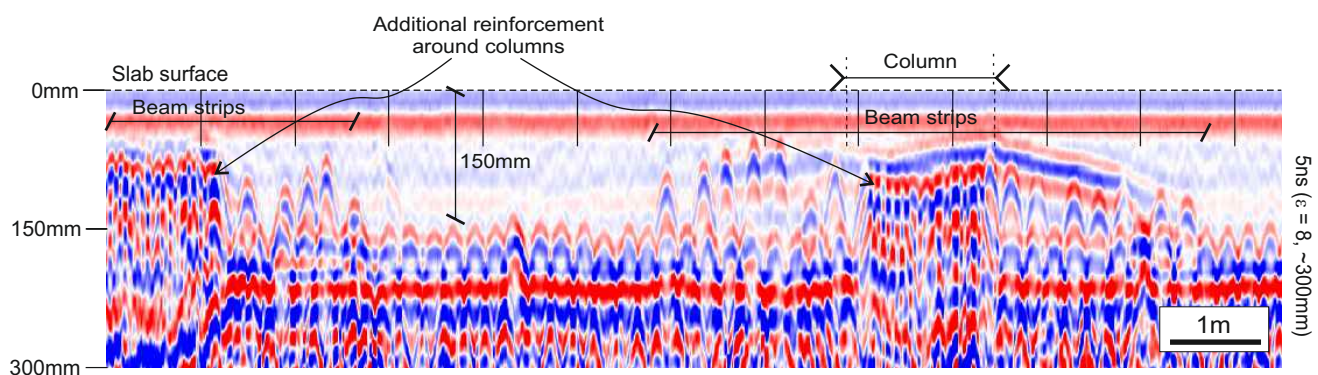
High frequency, high resolution surveys, provide a non-destructive testing tool for concrete and other construction materials, allowing their internal structure and flaws to be imaged in situ without coring or breaking out.

The capability of modern equipment and software to acquire and process large 3D volumes of data mean that a great deal of detailed information can be obtained from a GPR survey.

High frequency GPR allows rapid non-destructive coverage, capable of imaging multiple layers of construction detail, voids and flaws, and the location of internal metalwork including multiple layers of reinforcement.



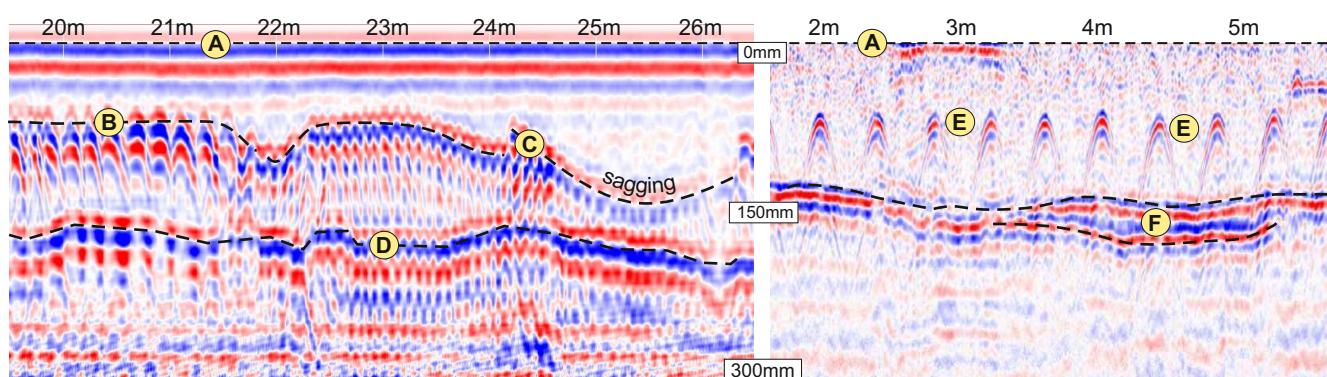
Summary of findings from a Car Park in Central London



A typical radargram recorded in the investigation with annotated interpretations

Whereas traditional cover meters are somewhat limited in their penetration depth and their application to complex reinforcement arrangements, a 900 to 2000MHz GPR system can provide high resolution data to depths of 1000mm and provide a permanent record of reinforcing mesh (see examples **below** and

next page). The resulting radargrams can highlight variations in bar spacing and areas of poor mesh placement (sagging or shallow cover depth). In the examples below, reflections from the slab base are also clearly in evidence providing important data on the slab thickness and sub-slab flaws.



Key
features

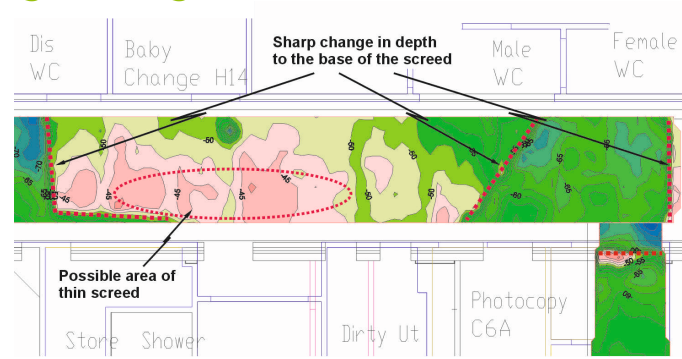
- Ⓐ Surface of concrete slab
- Ⓑ Rebar at 200mm interbar spacing
- Ⓒ Rebar at 100mm interbar spacing and variable cover depth due to poor placement

- Ⓓ Base of slab with synthetic membrane
- Ⓔ Widely spaced rebar at 400mm spacing
- Ⓕ Delamination and voiding at base of slab

Survey examples - Screed, concrete and cover depth

Defining the depth of screed in building flooring

Screed is the top finishing layer on a concrete slab. GPR can be used as a reliable, rapid, non-destructive means of testing the thickness and offers total coverage. Here a contour map (right) of calculated depth to the base of the screed layer has been produced based on the reflection time of the radar pulse over the survey area. The screed layer is clearly defined in the radar data by a high amplitude reflection. The results show a general variation as well as some sharp changes in the depth to screed. Pink areas are those shown to be below the specified thickness of construction.



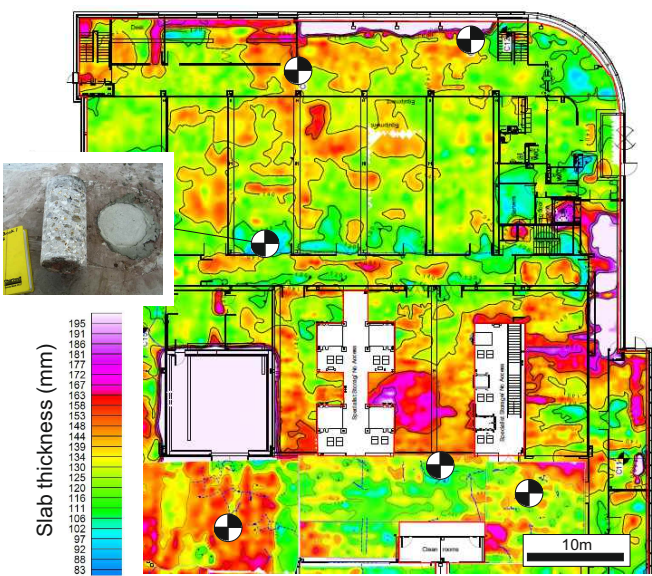
Blue indicates thicker screed (>75mm) whilst pinks show less than 45mm

Defining concrete slab thickness

In this example, GPR was used to determine the thickness of the concrete floor in a recently constructed industrial unit. The slab was suffering from cracking defects and it was suspected that the slab was not constructed to the specification of 150mm thickness. The GPR survey revealed large variations in slab thickness in excess of the accepted tolerance of 10mm typical for cast in-situ slabs.

Targeted coring was undertaken on anomalous features to confirm and calibrate the GPR survey. The GPR survey took several days to complete and resulted in the need for a much lower amount of destructive coring which was paramount due to the sensitive nature of the site.

Plan view map of floor slab thickness from the GPR data. The GPR data was calibrated using targeted cores (inset).



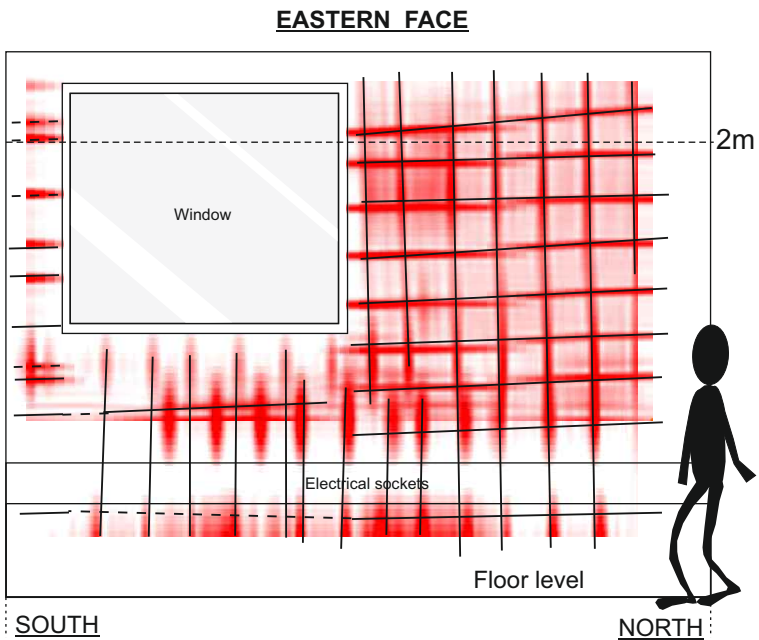
Defining the cover depth of rebar in a concrete wall

In this example shown right, high frequency GPR was carried out on a series of thick concrete walls to detect any defects in the concrete, gaps in the reinforcement and to check there was sufficient cover depth to the rebar. A sufficient thickness of concrete cover is required in order to slow down the carbonation process towards the rebar and prevent corrosion and spalling. In the UK this depth is typically 50mm. The use of calibrated GPR to verify this across the entire surface reduces the need for any intrusive breakouts and helps to target where future maintenance may be required.



Linear radar reflection indicative of location of reinforcement bar in concrete wall

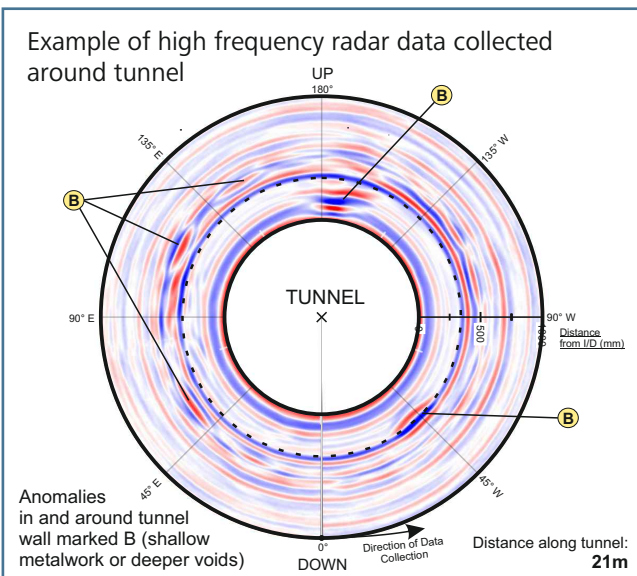
Average cover depth to reinforcement layers	
Vertical	96mm ± 7mm
Horizontal	78mm ± 24mm



Survey examples - Voids in structures

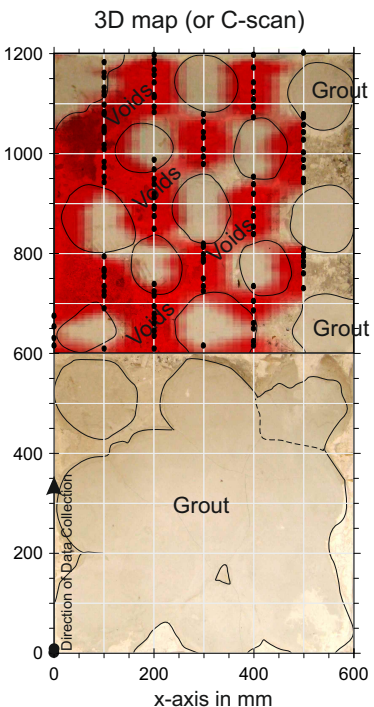
Voids behind a water tunnel

In the example **below** a high frequency radar scan utilising a 1.5GHz and 900MHz GPR antenna was undertaken using radial and lateral scans along a length of tunnel subject to water ingress. The 2m diameter tunnel, which linked two of the largest storm water tanks in the UK was 40mbgl and was constructed of glass fibre reinforced pipe surrounded by bolted segmental concrete panels. The likely presence of voiding in the surrounding ground was detected in the data, which was used to target remedial grouting.

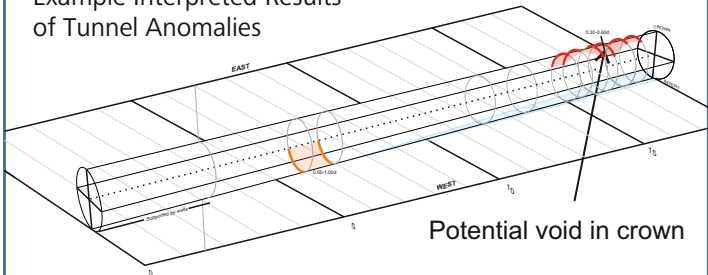


Detecting voids under floor tiles

The stability of floor tiles is based on the appropriate use of grout. Too little grout can cause movement and cracking. In the example **right** a high frequency 2GHz radar scan was used to successfully show voids between the grout, which enabled the client to target and inject further grout/resin to prevent further movement.



Example Interpreted Results of Tunnel Anomalies



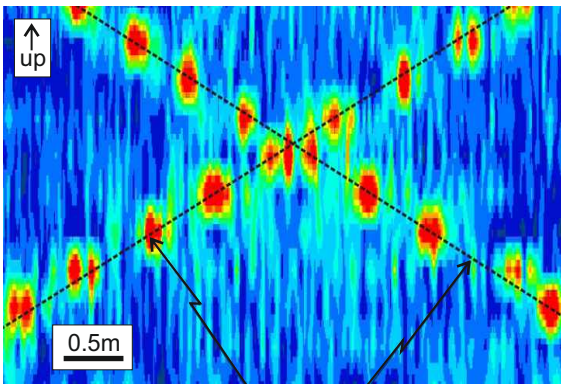
Detection of internal metalwork and voids

Here a GPR survey was used to determine the nature of the internal structure of walls at a university building. The survey (see photo **below left**) was undertaken using a high frequency 1.5GHz antenna at a 25cm line spacing to provide high resolution images of the wall interiors.

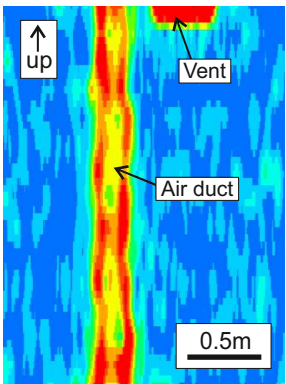
The survey was highly effective in showing areas of wall that contain internal metalwork (**below centre**). GPR has also been used very effectively in locating cavities and voids within structures. The radar time slice (**below right**) shows a metal flue which runs up the interior of the wall.



GPR data collection by hand



High amplitude reflections (coloured red) at 60mm cover depth indicate metal bracing in wall



Time slice at 140mm depth shows vertical air duct in wall

The application of GPR to the non-destructive investigation of Historic Buildings

The utility of the GPR (Ground Penetrating Radar) technique in the investigation of historic buildings is gaining increasing recognition. 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.

Particular success is also recorded in the measurement of material thickness in construction layers such as facing stones.

Suitably qualified geophysicists may also need certified confined space training, rope access training or other site specific access passes in order to gain access to various sites.



GPR can be used successfully to investigate listed buildings where minimal disturbance to the fabric of the structure is of paramount importance.

Left, the facades of a listed building in Finsbury Circus, London is surveyed for internal metalwork. **Right**, GPR is conducted on the bascules of Tower Bridge to locate areas of increased moisture content as part of major refurbishment works.

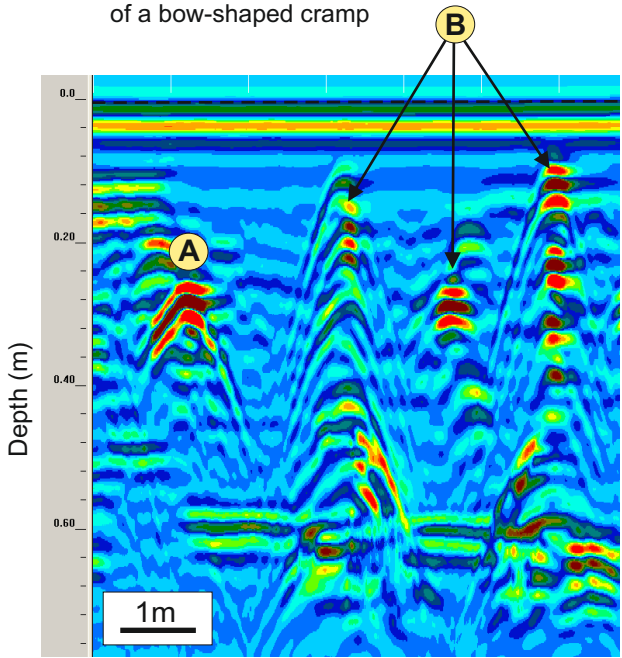
Survey example

GPR Survey of an Old Town Hall

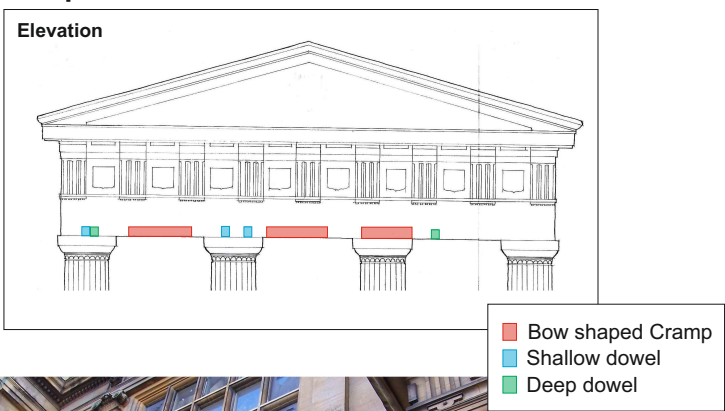
Here a GPR survey using a 1.5 GHz antenna located metal fixings within the columns and lintel of the town hall facade. **Below** is an example radar trace displaying the different types of reflections recorded. It is possible to identify the type of metal structure

from the reflection. The diagram opposite summarises the interpretation. The interpreted data suggest that corrosion of the metal fixings could be the cause of cracks appearing in the stonework of the Town Hall.

- A** High amplitude hyperbolic reflection possibly indicative of a dowel
- B** Group of three high amplitude hyperbolic reflections possibly indicative of a bow-shaped cramp



Interpretation



Geophysical Techniques Available

- ✓ Ground Penetrating Radar (GPR)
- ✓ Electromagnetic Location (EML)
- ✓ Electromagnetic (EM) Ground Conductivity
- ✓ Magnetic Gradiometry



SafeGround is the service and utility detection and mapping arm of RSK's geophysics team.

Utility mapping is a non-intrusive method of accurately obtaining and verifying data about buried utilities. Most site works and new developments require a utility survey to establish the location of assets such as underground pipes, cables and other buried obstructions in order to inform a safe ground investigation, and the design of the project. This approach can ensure that costly accidental strikes to buried utilities are avoided.

There are a number of guidance documents in the UK related to utility mapping, including HSG47 Avoiding danger from underground services, and British Standards Institution PAS 128, Specification for underground utility detection, verification and location.

RSK provides utility surveys compliant to PAS 128 specifications. As described in the following pages, PAS 128 sets out the accuracy for capturing the data and assures the quality of survey from the desk top study through to verification. PAS takes a hierarchical approach to survey types, providing different levels of detail, confidence and cost depending on the client's needs.

The PAS survey types include:

- **Survey type D** – Desktop utility records search
- **Survey type C** – Site reconnaissance
- **Survey type B** – Detection survey using geophysical techniques
- **Survey type A** – Verification survey

It is important to agree with the client the survey type and detection method to be undertaken prior to commencing works. Other practitioners may offer a different level of service and deliverable so it is important to understand any differences at the outset. The variable quality available in the utility mapping marketplace is of real concern to reputable organisations. Contractors deploying unqualified staff who use geophysical equipment incorrectly have tarnished the reputation of utility mapping specifically, and by extension also other geophysical surveys. The client should be sure of the qualifications and experience of the staff contractors use.



From Utility Strike Avoidance Group (USAG)

A typical pavement can hide a myriad of buried utilities (right). Accurate locating of utilities is required to avoid costly strikes (above)



SURVEY TYPE D – Desktop utility records search

A utility search desktop service involves obtaining information to identify existing utility data within a search area from all the statutory utility asset owners. RSK are able to provide a report which includes all the responses including plans/records of existing utilities from both affected and non-affected utility owners for the search location in one streamlined package.

- Identify asset owners and request asset information for collation
- Report includes plans and (if requested) a combined overlay onto a topographic CAD drawing
- Positional accuracy – undefined
- A pre-requisite of a full site survey



Why carry out a buried utility survey?

Strikes on underground pipes and cables cost the UK £1.2bn a year. Worldwide there is an estimated 275,000kms of gas pipe, 353,000kms of sewers, 482,000kms of electricity cables, 450,000kms of water pipes and several million kilometres of telecoms and street lighting. The location of many of these utilities is unknown or recorded on inaccurate plans at best. Therefore, a precise understanding of the ever increasingly complex subsurface infrastructure is of huge importance to ensure pre-site work health & safety risks are managed effectively and to reduce disruption to everyday business and societal activities.

SURVEY TYPE C – Site reconnaissance



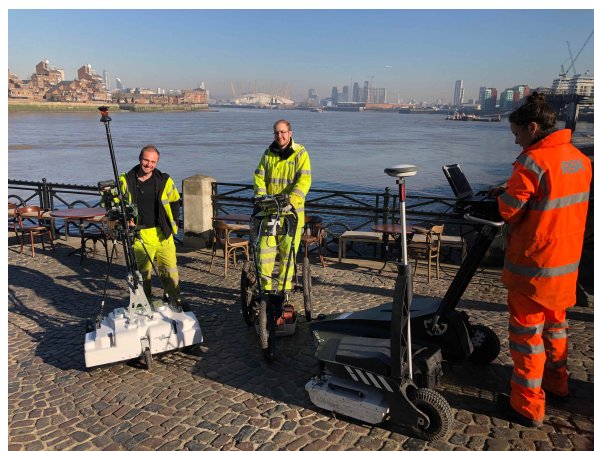
Involves a site visit where existing records are supported and validated by the visual inspection of physical evidence (such as inspection covers, valve covers, surface scars and marker posts) observed during a site visit.

SURVEY TYPE B –

Detection surveys – M1(P) to M4(P)

Several detection methods are applied to any one survey area (a minimum of Ground Penetrating Radar (GPR) and Electromagnetic Locating (EML) is typically deployed – although other geophysical methods may also be used)

- Methods include EML, GPR & other geophysical methods
- Mark out of utilities on site
- Post process collected data
- Report includes a CAD plan
- Good positional accuracy – up to $\pm 15\%$ depth with multiple techniques



1 A range of GPR systems can be deployed

Methods for utility detection

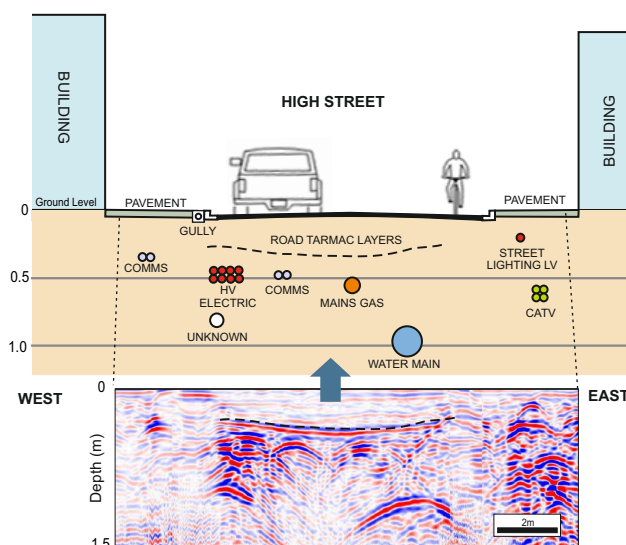
1 Ground Penetrating Radar and PAS Survey Levels

The detection of buried utilities is the most common application of GPR. GPR is useful in particular for locating non-metallic services such as plastic and ceramic pipes, and ducts, which traditional cable locators cannot detect.

GPR surveys are carried out in a grid of orthogonal lines across the area of interest. Buried services generate hyperbolic reflectors in the GPR data (see **right**) from which can be traced across the site as linear features. GPR detection methods are selected taking into account the density of the expected buried services and whether post processing is carried out. Transect line spacing ranges from 0.5m (M4P) to 5m or more (M1P) depending on the complexity of the buried infrastructure present. A typical urban GPR utility survey comprises a M3P survey with survey lines conducted on a grid of lines at 1m spacing.

Hand pushed karts are typically used to provide GPR data at high scan rates and in tight to reach places such as pavements. On highways and complex sites, large density arrays can be deployed (typically vehicle towed) to increase survey speed (see **below**) and reduce site time due to the speed of data collection.

A Schematic interpreted cross-section from GPR data

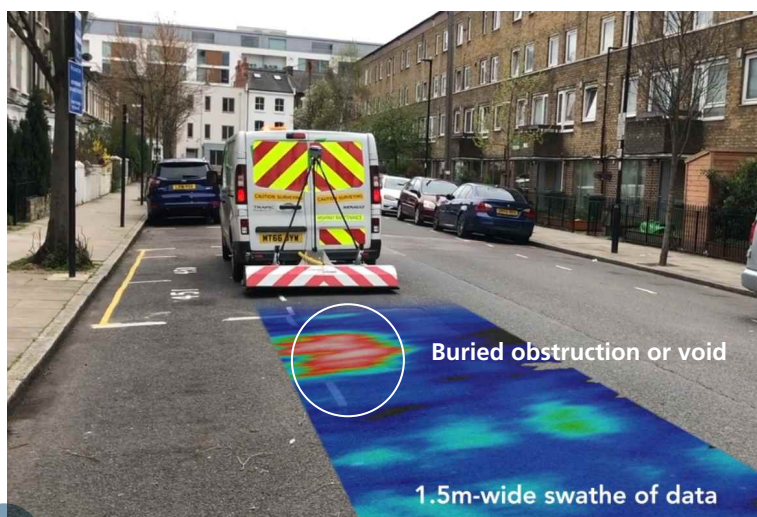


B Example 400MHz radar data showing reflections from buried services across a typical urban road

3D GPR Arrays

Traditionally, GPR surveys have been carried out by single channel antenna in grids with survey lines in two orthogonal directions. RSK's latest state of the art equipment includes massive array GPR systems such as the IDS Stream C system with 34 antennas in two polarisations and the Raptor which can be vehicle towed at full traffic speed (see **left**). Both systems only require a single pass to collect a swathe of data to the highest survey level and can be deployed on a range of sites where access time may be limited. Use of the array allows an increase in productivity whilst maintaining accuracy and quality, with a reduction in site time due to the speed of data collection.

C Vehicle towed GPR systems provide the highest PAS survey level



2 Electromagnetic Location (EML)

EML involves the passive and active detection of utilities using a hand held receiver using electromagnetic and radio frequency signals that are present in metallic utilities, and detection of magnetic fields produced by loaded, unbalanced electric cables. Signals can be induced from a transmitter at the ground surface, by direct connection from a signal generator or from a sonde or tracing wire placed in the pipe or duct (active EML). EML methods are deployed over the full area. Signals traced with the EML method are marked on the ground surface and located with a high precision GPS or total station equipment for accurate display on drawings of the site.

GPR Processing added value

The P suffix denotes post processing of the GPR data which is carried out by experienced and qualified RSK geophysicists in the office. The processing improves the interpretation by using algorithms and filters to better resolve multiple targets of interest in the data, which may otherwise be missed by on site mark out surveys alone. This allows us to gain a better understanding of complex areas and provides an auditable record of what was carried out. Post processing of GPR data is recommended to be carried out in most surveys.

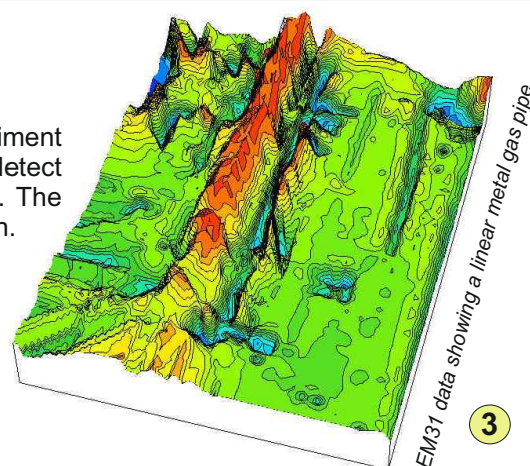


- + Passively detects power and radio signals from electric cables and metal pipes (**below**)
- + Actively connect on to tracer cables and metal pipes (**below left**)
- + Trace sewers and ducts with sonde and tracers (**below right**)



3 EM Conductivity and other geophysical methods

Use of other geophysical methods for utility detection is often deployed to compliment GPR methods. For example magnetics or electromagnetics may be used to detect deeper metallic pipelines, services and the presence of underground tanks. The combined use of multiple methods adds to the confidence of successful detection.



SURVEY TYPE A – Verification

Verification surveys are where underground utilities are observed and located at a manhole or inspection chamber, or are physically excavated, exposed and recorded. RSK leads the way in innovative, safe digging technology with the introduction of vacuum excavation (see **right**) which can be used to create inspection pits to expose known or suspected live services without risk to human health.

- Visual inspection in manhole chamber, or directly expose a utility using inspection pits or trenches
- Hand dug pits, or vacuum excavation are a safer method than mechanical excavator to protect integrity of utility
- Accurately measure horizontal and vertical position to $\pm 25\text{mm}$

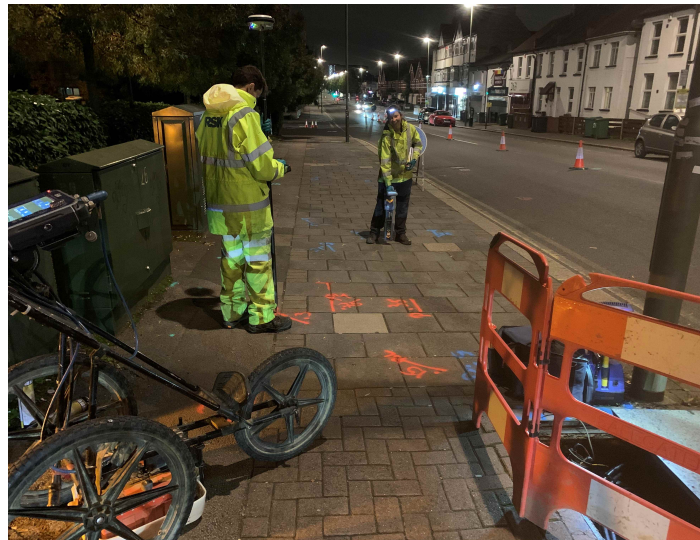


Hydro-vac excavation can be used to safely expose buried live utilities.

Quality Levels

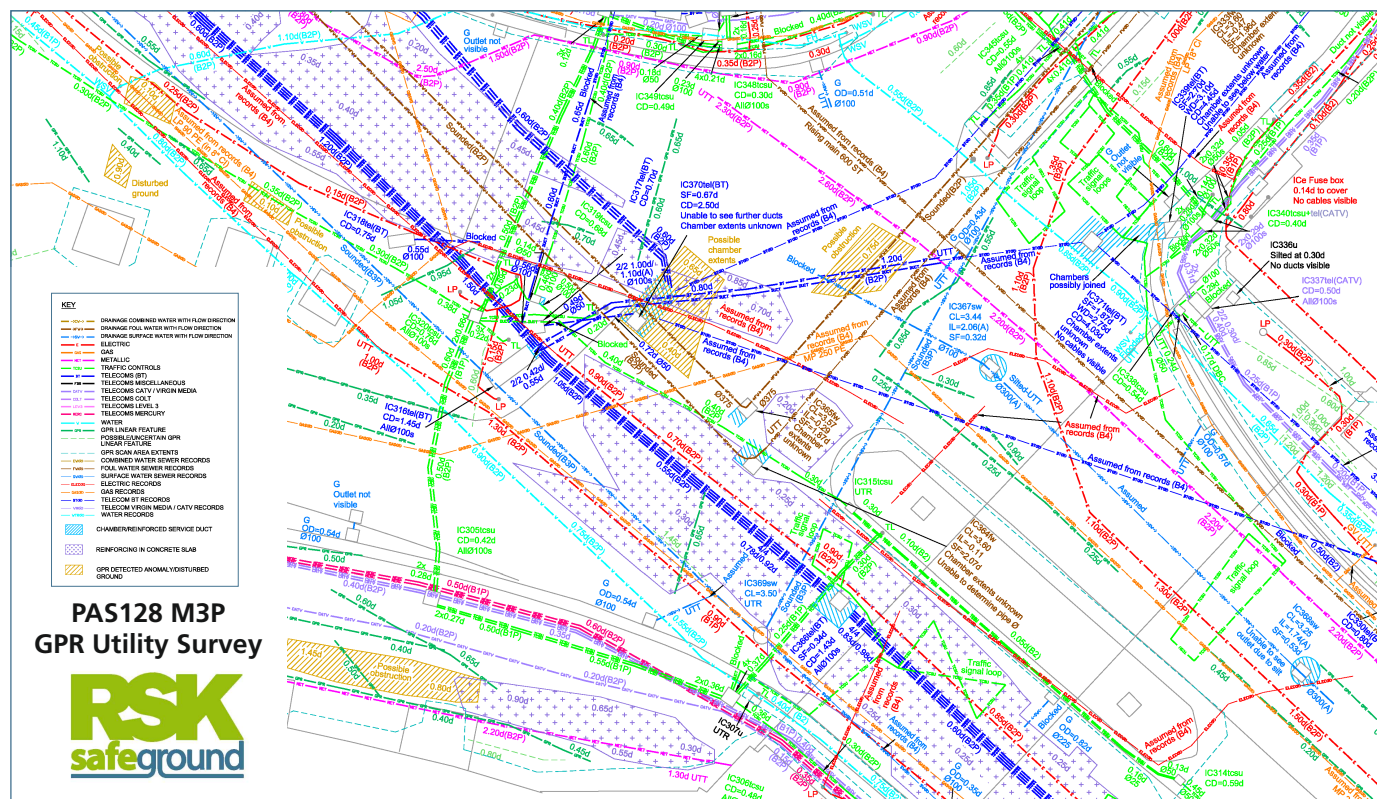
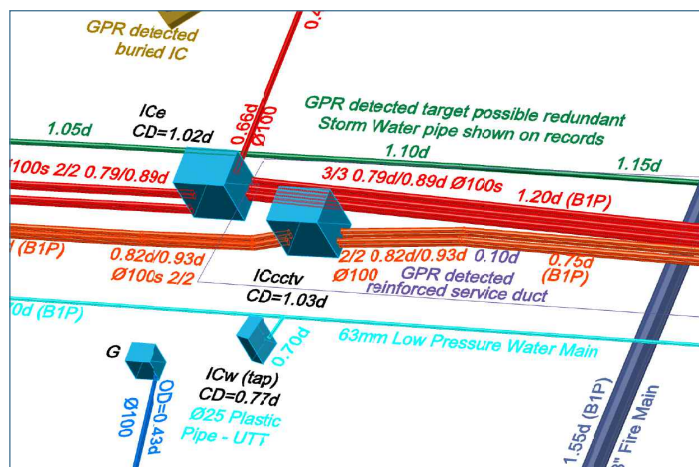
The quality level is a classification applied to each segment of a utility surveyed based on location accuracy and survey method to reflect the confidence level of detection. For PAS survey type B there are 4 quality levels from QL B1 to B4. B1 means the utility is detected in two methods with a high confidence of position and depth, B2 by at least one method but at a lower confidence of position, B3 as B2 but with no depth information, and B4 means there has been no positive identification of the service and it's position is assumed from records. The levels are marked on each segment of the service lines on the utility drawing.

Top right; on completion of the GPR and EML survey, the locations of marked out survey grids and traced utilities are recorded with high precision GPS and total stations



Deliverables - Example interpretative results plan

On completion of the GPR analysis, information from the EML tracing, cover lifting, visual inspection, together with existing statutory records are combined and overlain over existing site plans, and 2D CAD (**below**) and 3D CAD (**right**) drawings produced showing the location of all detected services on site, their depths, quality levels and key asset information to provide the most comprehensive drawing possible of the buried infrastructure present on site.



UNEXPLODED ORDNANCE (UXO)



Geophysical Techniques Available

- ✓ Surface Magnetics
- ✓ Borehole Magnetics
- ✓ Time Domain Electromagnetics (TDEM)
- ✓ Ground Penetrating Radar (GPR)

Unexploded Ordnance (UXO) and Unexploded Bombs (UXBs) are explosive weapons that did not explode when they were employed and still pose a risk of detonation. There are many sources of UXO contamination - most originate from wartime however more recent sites such as military training grounds can also hold significant numbers.

10% of bombs dropped during WW2 did not explode. In the UK 60 bombs are found every year, the majority in sites undergoing new development. It is therefore hugely important to understand the hazards and risks early in the development of a site in order to avoid costs and delays.

Detection Surveys

In order to determine the most effective geophysical detection methods on a site, consideration is given to a number of factors, including UXO target type and size, anticipated burial depth (cm to many meters) and type of ground conditions present at the site. Where shallow buried UXO may be present, a non-intrusive surface detection survey using one of more techniques may be appropriate (See below). For deeper targets in-hole detection magnetic methods may be deployed. This is typically undertaken with a magnetometer probe (see **far right**) at discrete intervals down a borehole during drilling works to detect the presence of deeper UXO.

A surface **magnetometer** survey is the most commonly used technique for detecting shallow ferrous UXO in the top 2-3m of ground (see **right**). **TDEM** methods can also be deployed to detect both ferrous and non-ferrous objects. Using both techniques can provide a higher confidence in the detection of UXO. Both survey types can be undertaken with instruments on foot or using towed arrays to rapidly cover larger sites.

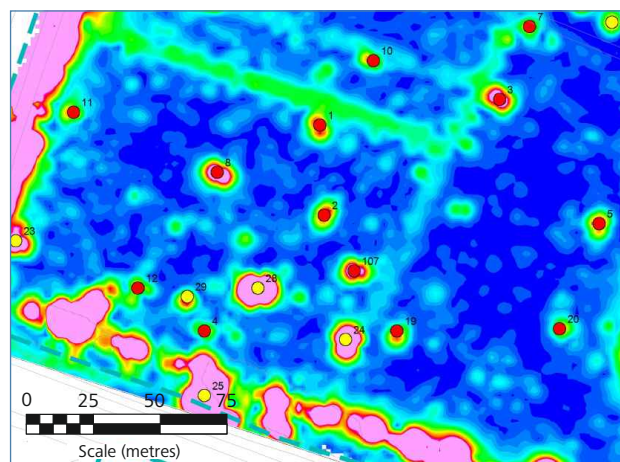


Image from CIRIA.
Urban areas pose a high UXO risk

As part of the management of UXO risks on development sites (CIRIA C681) the findings of a thorough and detailed desk study and risk assessment are used to inform any survey (if required), therefore ensuring that the correct UXO detection techniques are employed.



Detection of UXO with surface magnetics (left) and downhole magnetics (right)

Data Processing and Interpretation

When conducting UXO investigations, data quality and targeting accuracy are key to effective characterisation and remediation of UXO sites. Without further analysis or investigation it cannot be determined from the data alone whether an object is of UXO origin or is scrap metal. RSK uses advanced analysis and modelling software on each magnetic and TDEM anomaly where needed to determine its characteristics including amplitude, size, and likely depth in order to establish its likelihood of being UXO.

Depending on the findings of the above, an intrusive target investigation may be required to further mitigate the remaining potential UXO risk.

TDEM contour map of part of a former airfield showing the location of possible buried metallic objects and UXO (red circles)

Geophysical Techniques Available

- ✓ Ground Penetrating Radar (GPR)
- ✓ Electrical Resistivity Tomography (ERT)
- ✓ Seismic Refraction
- ✓ Multi-channel Analysis of Surface Waves (MASW)
- ✓ Microgravity

Critical infrastructure is the backbone of our nation's economy. The UK's national infrastructure is defined by the Government as: "those facilities, systems, sites and networks necessary for the functioning of the country and the delivery of the essential services upon which daily life in the UK depends".

Critical sectors include transport and energy which include key elements of infrastructure – such as a physical asset such as a road, railway line or pipeline - the loss or compromise of which would have a major detrimental impact on the availability or integrity of essential services, leading to severe economic or social consequences or to loss of life.

Geophysical surveying plays an important role in the investigation of these physical assets offering solutions across the full life cycle of the infrastructure – from the planning of new routes, designing and construction, through to the ongoing monitoring and maintenance and repair works. Geophysical surveying techniques are uniquely beneficial because they are rapid to deploy, less disruptive, and non-invasive and thus have a lower impact on the environment than conventional drilling methods.

Survey examples

Multi-technique railway investigation

Many of the UK's railway embankments and structures date from the Victorian era and are in a poor condition. Often there are minimal or no records. A combination of GPR, ERT and MASW can provide crucial insight into the state of the sub-grade and built structures. A significant thickening of ballast for example can show areas of ground failure (See example **right**). ERT and MASW can provide insight into areas of soft saturated clays, voids and hidden unrecorded structures (see example **below**). Anomalous areas can then be targeted for further investigation and repair.

Applications

- ✓ Mapping of buried utility infrastructure
- ✓ Determining thickness of construction layers (such as highway pavement, railway ballast)
- ✓ Locating basements, arches, culverts and mineworkings
- ✓ Locating sinkholes, solution features and natural voids
- ✓ Locating voids made by burrowing animals
- ✓ Mapping bedrock and geological conditions

GPR in Road Pavement Assessment

GPR is commonly used at high speed on highways in order to provide information on the type, thickness and condition of the road construction layers. Data acquisition can be rapid with state-of-the-art vehicle mounted systems (see **below**).

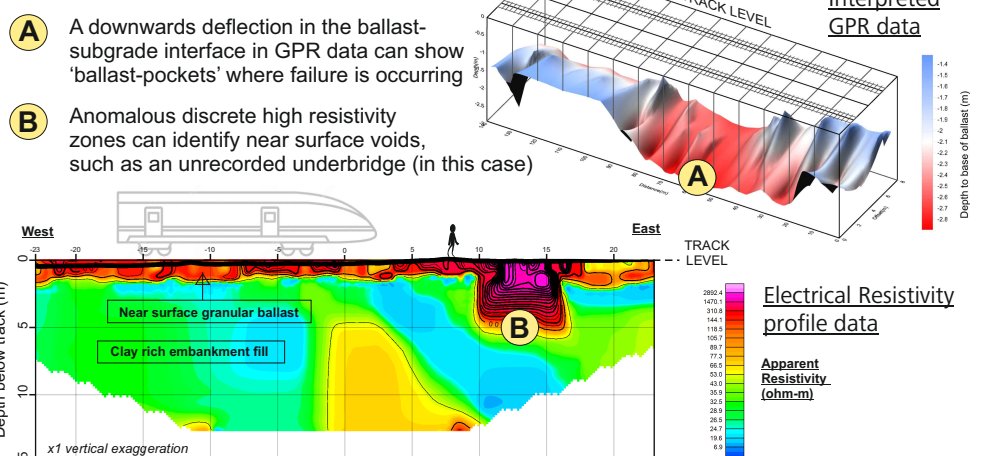


Vehicle mounted GPR systems can provide huge productivity benefits on highways with limited access



Deeper investigation

In both rail and road environments, profiles of hand pulled lower frequency GPR and microgravity can investigate to deeper depths to reveal hidden voids in areas of concern. When calibrated with cores and boreholes, geophysical methods can provide a continuous measurement profile which can be repeated over time to provide an indication of performance as part of maintenance and renewal monitoring programmes.



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Need further help or advice?

We are happy to advice on principles and techniques. Feel free to contact us.

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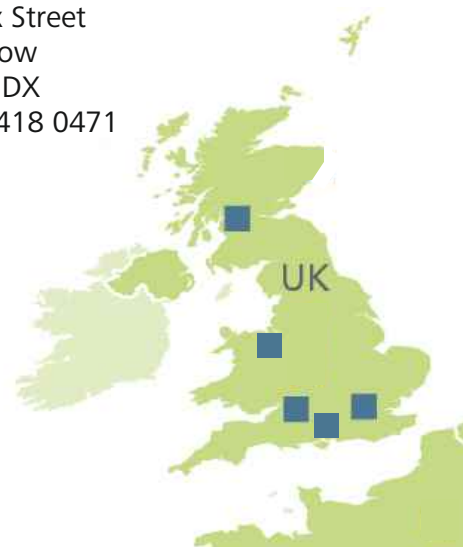
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This book has been produced by RSK's experts in site investigation, with grateful thanks to our many clients who gave us such interesting sites to investigate.

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