Interreg North-West Europe NWE-REGENERATIS
European Regional Development Fund

WP T1. D3.1 Benchmark report on geophysics and non-intrusive investigation techniques

15 October 2020

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Final Version

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EXECUTIVE SUMMARY

Site investigations are traditionally carried out by drilling boreholes through various strata, logging of boreholes, sampling of strata and laboratory testing to assess engineering properties and infer behaviour of slopes, soft soils, embankments and foundations. Geophysics is still not used as a standard tool in the characterization and monitoring of landfills and brownfields due to the perception that it is not a well-established science or that the results are unreliable. This report provides a summary of how non-intrusive geophysical techniques can be integrated to an engineering approach when investigating landfills and brownfields soil composition. This is demonstrated by filed case studies for site investigations and earthworks quality assessment. The variety of geophysical methods available for site investigations, their applications and interpretations are presented. The report describes how the cost of investigations and the risk of unplanned ground variations can be reduced by integrating geophysical methods within a geotechnical investigation framework.

1 INTRODUCTION

The use of geophysical investigations supplemented with selective intrusive investigations at critical locations for site investigations offer an efficient and cost-effective means of obtaining an assessment of the subsoil strata and generate relevant high-quality data. One important outcome of site investigation should be to provide enough data to construct a robust and representative site conceptual model, which will further inform recovery and remediation options. The site investigation must therefore incorporate site history, localisation buried infrastructure, geology (including fracture systems where relevant), hydrogeology, dissolved contaminant and/or non-aqueous phase distribution, and the interrelationships between these components. Without such understanding, it is difficult to establish the spatial resolution of data needs and developing a contaminant management and/or contaminant recovery and therefore remediation strategy may prove less effective than intended.

Over the last two decades, a range of geophysical techniques (i.e. echo sounding, seismic wave measurements, electromagnetic methods, (micro)gravimetry, resistivity tomography, induced polarisation measurements, magnetic methods) have been used with success to deduce spatial variations of relevant geological and hydrogeological properties across a range of scales. In turn, they provide an improved understanding of the distribution and transport of contaminants in the subsurface.

Geophysical methods have a good spatial (both lateral and vertical) resolution and can thus be used to get information over large areas that could not be covered by punctual measurements such as boreholes. Hence geophysical surveying may be used to pinpoint locations within a site to target with conventional intrusive investigation, but by the same token they can be deployed to minimise the disruption caused by conventional intrusive method such as boreholes, trial pits, cores or breakouts. Therefore, intrusive and non-intrusive investigation techniques (viz. geophysical methods and infrared spectroscopy) are rather complementary than excluding tools; for example, boreholes can obtain direct information on water composition whilst geophysical methods can help expand these findings both vertically and horizontally. In each case, the appropriate geophysical technique must be used in the correct survey manner in order to maximise the ability of the survey to yield clear results. Surveys should be designed and undertaken by qualified and experienced geophysical professionals and should make full use of available instrumentation and software to provide the best possible interpretation in a timely and efficient manner.

Non-invasive geophysical methods and infra-red spectroscopy are ideal when a large area of subsurface needs to be characterised quickly and cheaply. The trade-off for this efficiency is the spatial resolution compared with other geophysical and traditional site investigation approaches (CL:AIRE, 2007). Another criticism levelled at non-invasive geophysics is that the data quality can be altered by made ground and associated infrastructure (e.g. buried services), as well as above ground infrastructure such as aerial electric cables, which can pose a problem when using electromagnetic and magnetic methods (CL:AIRE, 2007).

However, this criticism can be turned to an advantage. Many of these features are a barrier to invasive characterisation techniques, thus, their detection can guide the location of borehole/well installation or direct push investigations. Non-invasive geophysics offers the clear advantage of minimising the need to drill or dig up sites, which is particularly useful at active sites where access may be restricted. While some approaches measure ambient or naturally generated energy (passive techniques), most involve transmitting an energy (electromagnetic or acoustic) signal into the subsurface and measuring the amount returning to a receiver (active techniques).

In this report, geophysical methods that are commonly used in the context of urban mining are presented. Seismic methods, for example, can be used to map soil morphology and estimate its mechanical properties. Due to their robustness, electrical methods are widely used for geological and hydrogeological characterization (lithology, porosity, water content, …) but also to monitor dynamic processes such as fluid flow (*e.g.* contaminant migration) or biological activity (*e.g.* contaminant degradation). Electromagnetic methods also described in this document allow to quickly map changes in electrical properties related to different materials or different pore fluids, but also to image buried structures or objects. Finally, the potential field methods can be useful to detect buried magnetic objects or delimiting the extent of anthropogenic deposits and to determine the density of soil potentially affected by anthropogenic deposits.

2 SEISMIC TECHNIQUES

Seismic techniques utilise the ways in which vibrations travel through materials. The seismic methods can provide elements of interest to detect the thickness and position of the weathering layer, physical properties of the different materials, including mechanical characteristics and the state of cracking, fractures and other discontinuous elements. They can be classified in two main families: active and passive techniques. Active techniques measure seismic waves generated by a source, such as a sledgehammer struck against a plate or a vibrating plate mounted on a truck. In contrast, passive techniques do not require artificial seismic energy and mainly consists in detecting the natural vibrations of the earth. All seismic techniques aim at detecting seismic waves that can be classified in two main groups: body waves (including compressional waves called P-waves and shear-waves called S-waves) that pass through the bulk of a medium and surface waves that are confined at the interface between materials with contrasting mechanical properties (Reynolds, 2011). The propagation velocity of P and S-waves can be linked to elastic moduli and densities of materials through which they are travelling. These are parameters of interest to geotechnical engineers.

2.1 Active seismic

Main active techniques include seismic reflection, seismic refraction, multi-channel analysis of surface waves (MASW), spectral analysis of surface waves (SASW), continuous surface wave system (CSWS).

Seismic reflection involves measuring the time it takes for a seismic wave to travel from the location of the seismic source down into the ground until it encounters a material with contrasting mechanical impedance (defined as the density times acoustic velocity) where part of the wave energy is reflected to the surface where it can be detected with an array of receivers called geophones (**Figure 1**). The technique is used to infer the geological structures of the subsurface. Although seismic reflection is the most widely used geophysical technique, it is less used in near-surface applications where surface and refracted waves may mask the reflected waves. For such applications, other techniques such as Seismic refraction or MASW are generally preferred. Seismic refraction consists in measuring the time required by the waves refracted at the interface between materials with different acoustic impedances to reach the geophones. The technique is used to estimate the seismic velocities of the subsurface layers from which important factors such as rippability, rock strength or fluid content can be derived. Both P and S-waves can be targeted by Seismic reflection and refraction. The Multi-Channel analysis of surface waves (MASW) technique measures the surface waves generated from a source to finally deduce shear-wave velocity (Vs) variations below the surveyed area that is most responsible for the analysed propagation velocity pattern of surface waves. Under most circumstances, Vs is a direct indicator of the ground strength (stiffness) and therefore is commonly used to derive load-bearing capacity. Other techniques that make use of surface waves are the Continuous surface wave system (CSWS) and Spectral analysis of surface waves (SASW). These techniques both produce 1D profiles using a small array of geophones with the CSWS having the advantage of the ability to control the wave frequency through a vibrating plate. This element of control allows the operator to focus measurements on certain depths, such as depths that might correspond to a bedrock interface and gain a higher resolution of data.

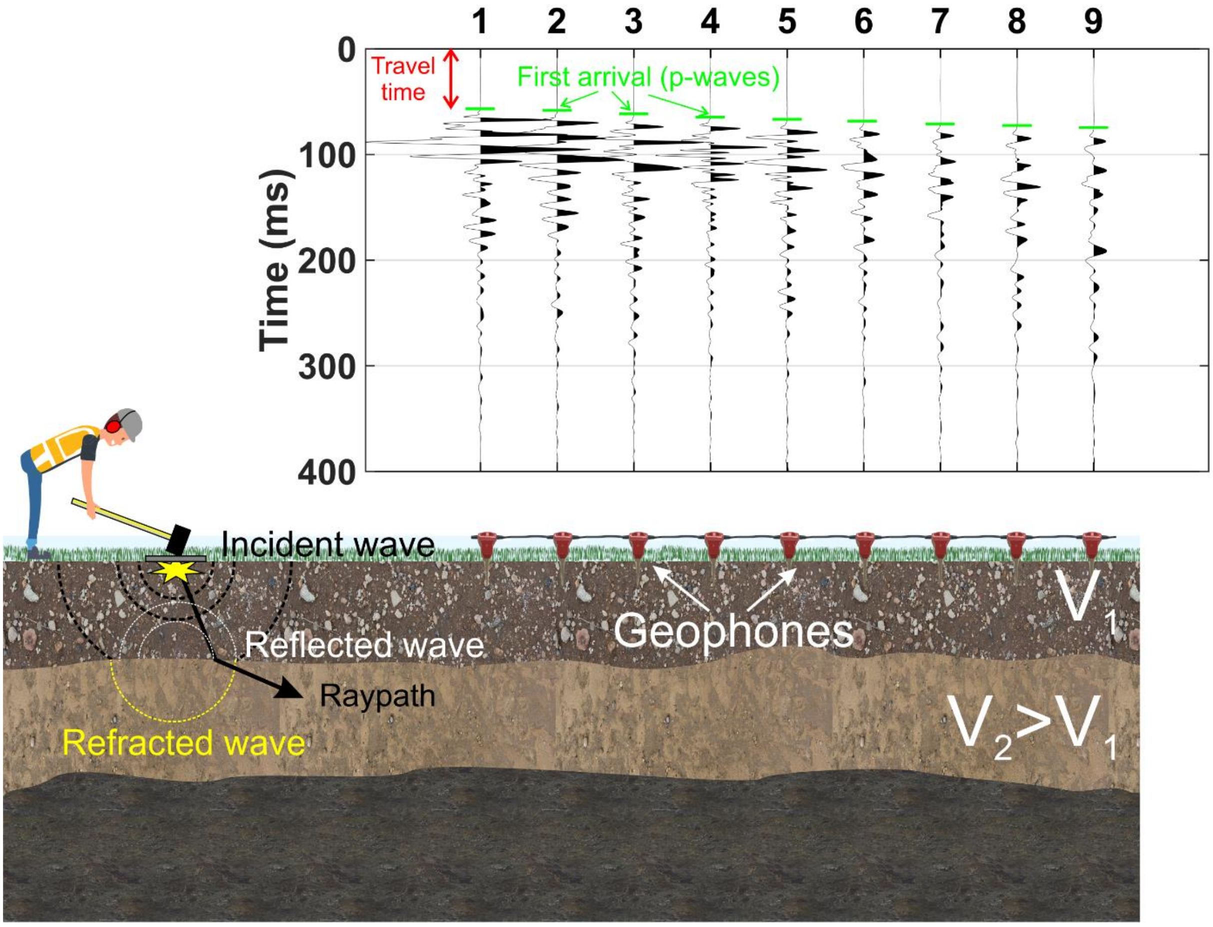


Figure 1: Diagram representing an active seismic acquisition. The seismic wave is generated by a source manipulated by the operator (here a mass struck against a plate). The wave packet generated contains p, s and surface waves that propagate at different velocities. The wave front created is detected by sensors called geophones. Seismic reflection technique uses the reflected waves to infer the geological structure of the subsurface. Seismic refraction rather uses the first arrival of seismic waves to infer the seismic velocities of the subsurface. Multi-Channel analysis of surface waves looks at the dispersion of the surface waves to infer shear-wave velocity distribution.

2.2 PASSIVE SEISMIC

Passive techniques such as the Horizontal to Vertical Noise Spectral Ratio (HVNSR or H/V) are used to map the depth of shallow layers. Data acquisition is done by measuring the ambient vibrations caused by natural or manmade sources using one (or more) sensor(s) recording the vibrations in 3 axial components for a given duration (typically 20 to 30 minutes for the HVNSR technique) (**Figure 2**). Assuming an impedance contrast between a low Vs material above a higher Vs layer, analysis of surface wave data collected in the frequency domain allows to estimate the thickness of the low Vs material. Passive techniques offer the advantages to be cheaper and easier to deploy than active techniques. However, they require high quality and/or large number of ground truth data (e.g. borehole data) to be properly calibrated.

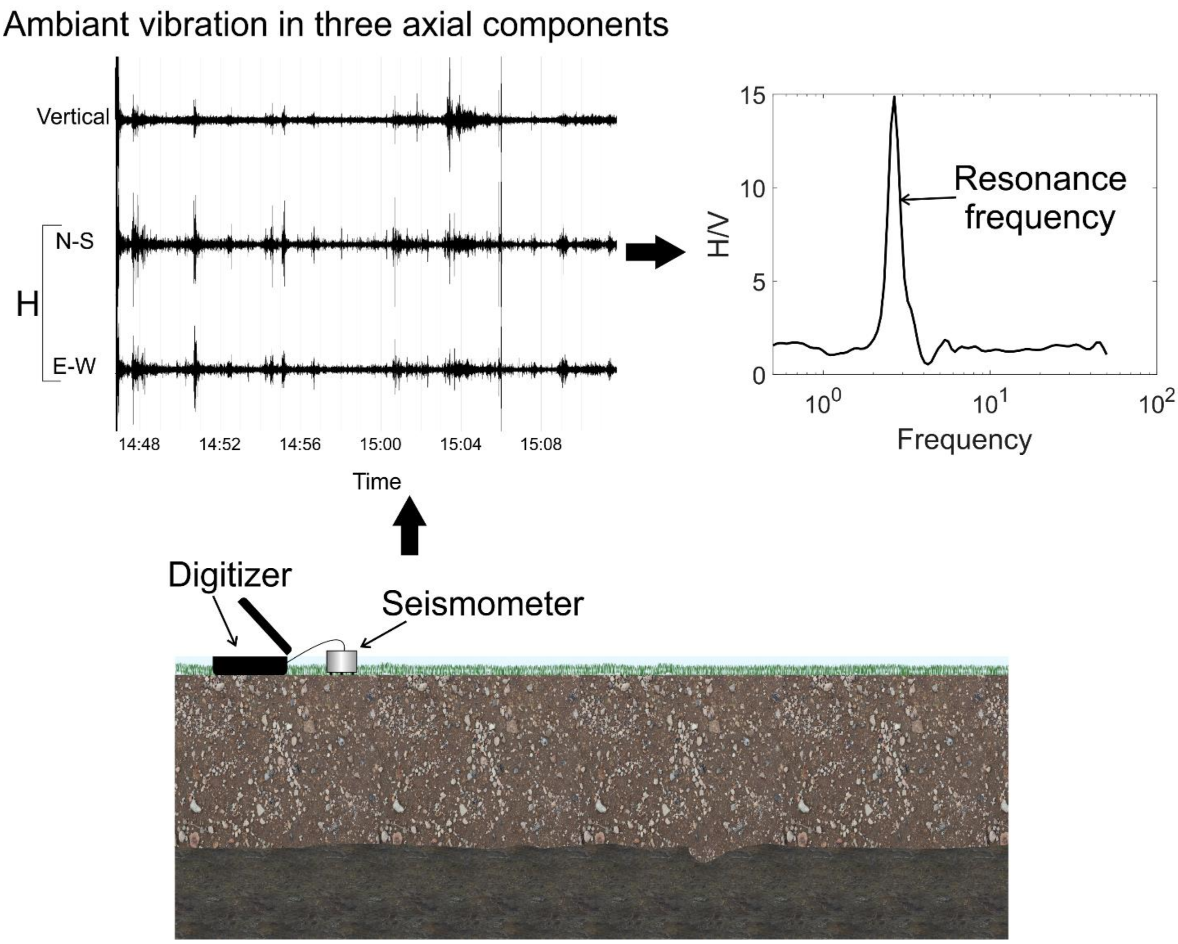


Figure 2: Passive seismic techniques allow ambient vibrations to be monitored using a seismometer. For example, in the H/V technique, the signal is recorded in three axial directions and the ratio between the Fourier amplitude spectra of the horizontal and vertical components is calculated. The frequency and amplitude of the resulting resonance peak depends on the depth and impedance contrast between a soft upper layer and a stiffer lower layer.

3 Electrical methods

3.1 Electrical resistivity imaging or tomography (ERI or ERT)

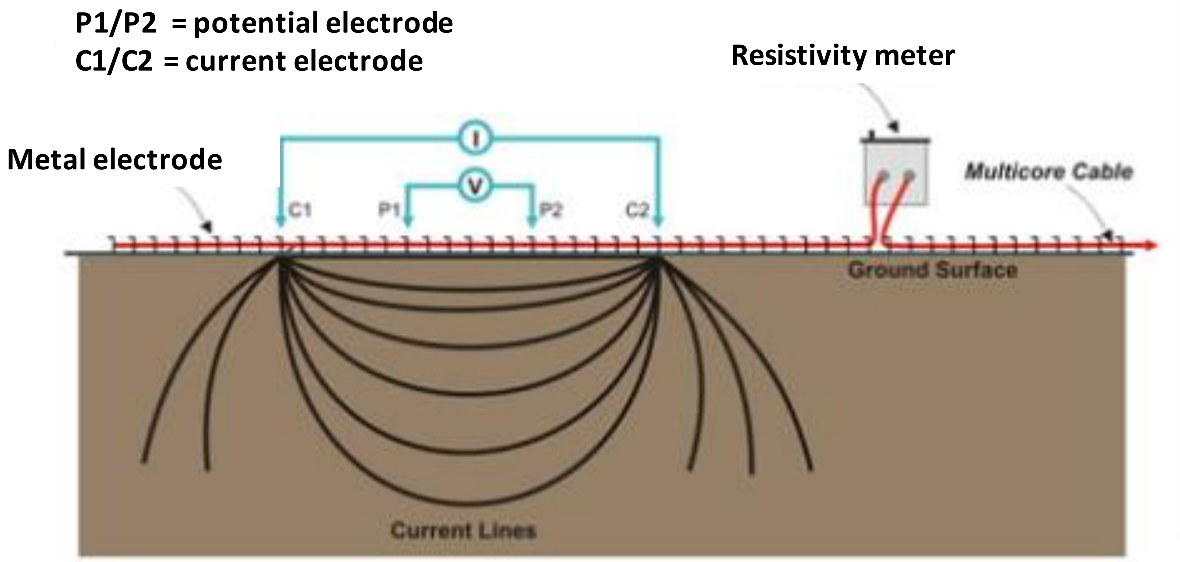
This technique, is also known as electrical imaging, aims to build up a picture of the electrical properties of the subsurface by passing an electrical current along many different paths between two current electrodes and measuring the associated voltage between many pairs of potential electrodes. An enormous number of electrode dispositions can be used in electrical resistivity imaging. Data in two-dimensional and three-dimensional forms thus can be obtained (Schwindt and Kneisel, 2009).

From these measurements, the ability of the different layers of the ground to resist the electrical current applied can be measured as the electrical resistivity. The ground resistivity is related to various geological parameters such as mineral and fluid content, porosity and degree of water saturation. Sedimentary rocks are usually more porous and have higher water content, thus they normally have lower resistivity values compared to igneous and metamorphic rocks. Unconsolidated sediments (overburden) generally have even lower resistivity values than sedimentary rocks. The resistivity value also depends on the type of minerals composing the ground layers. Indeed, clay and metallic minerals have lower are less resistive.

The two-dimensional electrical resistivity image (ERI), also known as electrical resistivity tomography (ERT) can be achieved from the collection of the data along a profile, with continuously increasing inner electrode spacing (pseudo-section) or as a series of successive vertical electrical soundings along a line. In practice, several electrodes with a given spacing between them are inserted into the ground along a line and various measurements are obtained for different electrode spacing (**Figure 3a**). The result is an image of the subsurface based on the resistivity changes in the vertical and horizontal direction along the survey line (2D model). Different ERI configurations can be found in **Figure 3b**.

Nowadays the most common practice to obtain the three-dimensional resistivity variation of the subsurface is from parallel two-dimensional lines whose data are interpreted with two-dimensional inversion algorithms and the results combined to generate a quasi-three-dimensional image. Due to the cost and time involved, three-dimensional surveying is not yet routinely employed for near-surface applications. In the full three-dimensional surveys, the pole-pole configuration is commonly used, and the electrodes are normally arranged in a square or rectangular grid with the same unit electrode spacing in the *x* and *y* direction). Ideally, the data must be collected from a set of survey lines with measurements in the x-direction, followed by another series of lines in the y-direction. The use of measurements in two perpendicular directions helps to reduce any directional bias in the data.

A)



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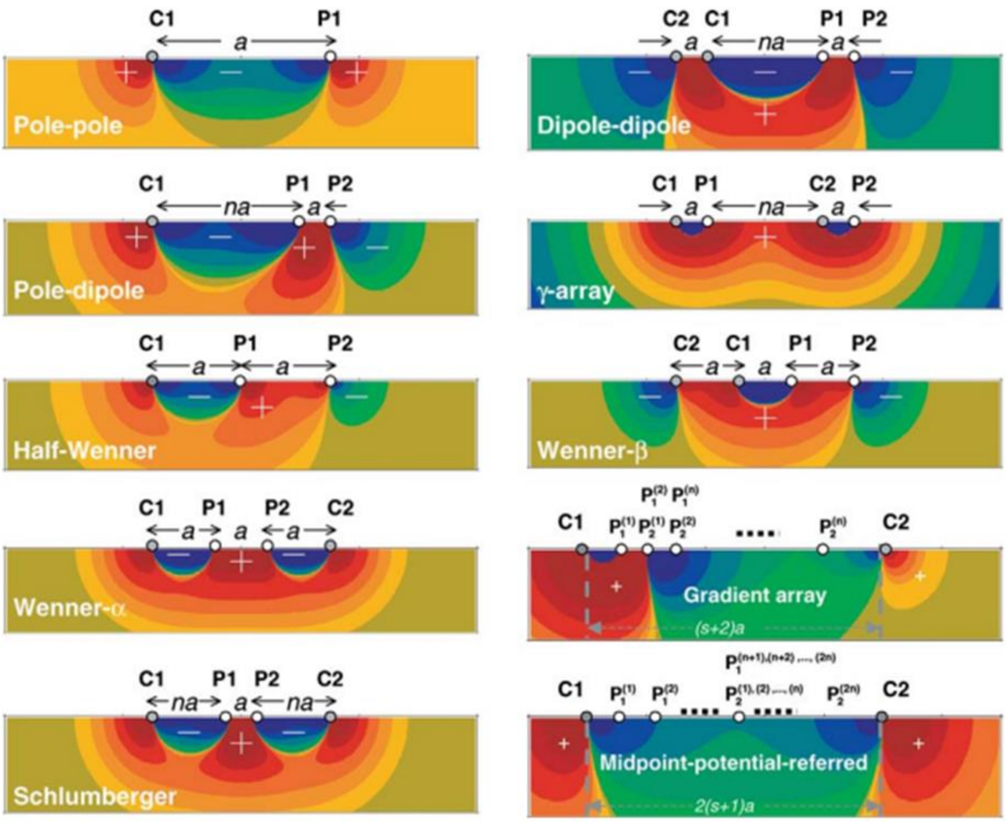

Figure 3. The acquisition principle electrical resistivity tomography (ERT) and induced polarisation (IP) techniques. A): This schematic depicts a four point measurement where a current is applied by the current electrodes (C1 / C2: positive and negative current electrodes, respectively) and the resulting voltage is measured by the potential electrodes (P1 / P2).B): Different types of electrode arrays and their sensitivity patterns (Dahlin and Zhou, 2004). An electrical current is injected into the ground via a pair of electrodes. The resulting difference of potential is measured at the same time at

two other electrodes. The ratio between the measured voltage and the injected current provides an electrical resistance via Ohm's law. The same process is repeated for a predefined combination of electrodes and at the end of the acquisition, the electrical resistance data are processed and inverted to provide an electrical resistivity model of the subsurface. The setup for time-domain induced polarization acquisition is the same. The difference lies in the fact that the voltage decay is measured and integrated after the current cutoff giving an additional data called apparent chargeability that can also be processed and inverted to provide the intrinsic chargeability model.

3.2 TIME-DOMAIN OR SPECTRAL INDUCED POLARIZATION

Polarization of a soil represents its ability to store and release electrical charges (Kemna 2000). Induced polarization (IP) measurements can be made in the time-domain (Time Domain Induced Polarisation or TDIP) or in the frequency-domain (Frequency Domain Induced Polarization or FDIP, also known as Spectral Induced Polarization or SIP). Both use the same field arrangement (i.e. that of conventional electrical resistivity measurements) but acquisition in the frequency-domain requires much more sophisticated systems (**Figure 3**). In the time-domain, as in an ERT/ERI survey, the voltage at the potential electrodes is measured during DC injection, but it is also measured after switching off the injection current. The voltage drop is not instantaneous, but rather has an exponential type of decrease that are linked to the ground layers polarization effects. Nowadays, most of acquisition system designed for ERI/ERT are also able to collect Time-domain IP data. In the frequency-domain mode, alternating current is used. Data collected in that mode consists in a magnitude (i.e. transfer resistances, R) and a phase shift between the applied current and the measured voltage. When phase and magnitude are recorded over a frequency range from 10^{-3} Hz to several kHz, this is referred to as Spectral induced polarization (SIP).

Although the mechanisms governing soil polarization are not yet totally understood and may have various origins, it is commonly accepted that electrochemical mechanisms are primarily responsible for the polarisation effect. In the low frequency range (bellow a few kHz), three main polarization mechanisms have been identified: (i) the electrical double layer (EDL) polarization accruing in the layers surround mineral grains and dependant on the nature of the grains; (ii) the membrane polarization varying with the grain/pore size distribution and (iii) the electrode polarization occurring in presence of metallic particles. The strong IP response observed in presence of electronically conducting minerals (e.g. galena, graphite, pyrite, ilmenite, etc.) makes it particularly suited to detect disseminated metallic ores. The method is therefore commonly used in mineral exploration. IP effect also occurs in presence of clay, organic matter, and organic contaminants.

4 ELECTROMAGNETIC METHODS

Two main categories of electromagnetic methods can be distinguished by the frequency of the transmitted waves. The low frequency category (from a few Hz to several kHz) includes electromagnetic induction techniques (e.g. Slingram or the Very-Low Frequency- VLF) whereas the high-frequency includes RADAR techniques (e.g. Ground Penetrating RADAR). All methods rely on the propagation of electromagnetic waves into the subsurface.

4.1 ELECTROMAGNETIC INDUCTION METHODS

Electromagnetic (EM) techniques can either use passive (e.g. magnetotellurics) or active signals generated by an artificial transmitter in the near-field (e.g. Slingram) or in the far-field (e.g. VLF technique) (**Figure 4**). The acquisition principle is the following for the active techniques: 1) a primary EM field is generated by a transmitter coil and propagates in all direction, 2) the primary field induces Eddy currents in the subsurface whose intensity is directly proportional to the electrical conductivity of the medium crossed by the waves. These currents in turn induce a secondary EM field which can be detected by a receiver. The receiver detects both the primary (that is emitted by the transmitter) and the secondary EM fields, which can also come from air sources. The secondary EM field differs in amplitude and phase compared to the primary field. The in-phase component with the primary field gives information about the magnetic susceptibility of the medium (i.e. presence of metallic object/structures) whereas the quadrature component gives information about its electrical conductivity. The depth of investigation of the techniques depends on several factors: distance between the transmitter and receiver coils, coils orientation, conductivity of the subsurface, and frequency of the transmitted EM wave. Given the properties targeted (electrical conductivity and magnetic susceptibility) the method is well suited to investigate PMSD in search for mineral resources but also to map contaminated land. Typically, EM systems are coupled to a GPS for precise positioning. Whenever possible, an acquisition grid is setup over the area to cover with an interline spacing depending on the size of the structure/object to detect. The method is cheap, easy to deploy and fast. However, measurements are sensitive to local disturbances (power lines, fences, railways, vehicles, etc.) and drift, especially the in-phase measurements. That is the reason why the calibration phase is key, so that information on magnetic susceptibility can be obtained and incorporated in further evaluation (RSK Handbook). Moreover, EM devices that cover large areas have a limited frequency and spacing range, with a vertical resolution between *ca*. 3-6 m depth per measurement (RSK Handbook).

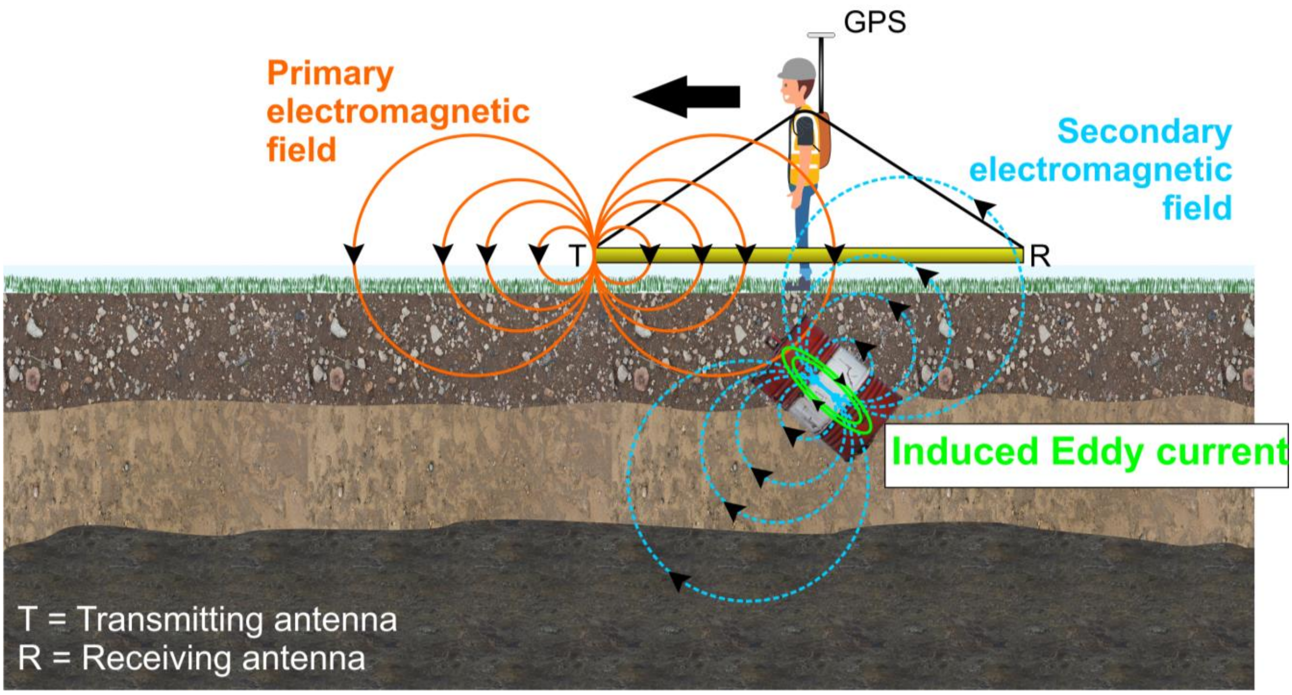

Figure 4: Diagram showing the basic principles of an electromagnetic induction survey. The acquisition system is composed of several antennae. The transmitting antenna generates the primary EM field that induces Eddy current in conductive objects/structures. The Eddy currents in turn create a secondary EM field that can be detected by one or more receiving antennae. The in-phase component of the received signal in relation to the transmitted signal is related to the magnetic susceptibility of the subsurface whereas the quadrature phase component is related to its electrical conductivity. The system is moved across the survey area, usually over a regular (geo-located) grid, and/or with a GPS antenna to provide locational information.

4.2 GROUND PENETRATING RADAR

Ground penetrating radar (GPR) is a high-resolution technique that allows obtaining an image of subsurface structures using electromagnetic waves in the frequency band of 10–2600 MHz. Therefore, signals of relatively short wavelength can be generated and radiated into the ground to detect anomalous variations in the dielectric properties of the geological material (**Figure 5**).

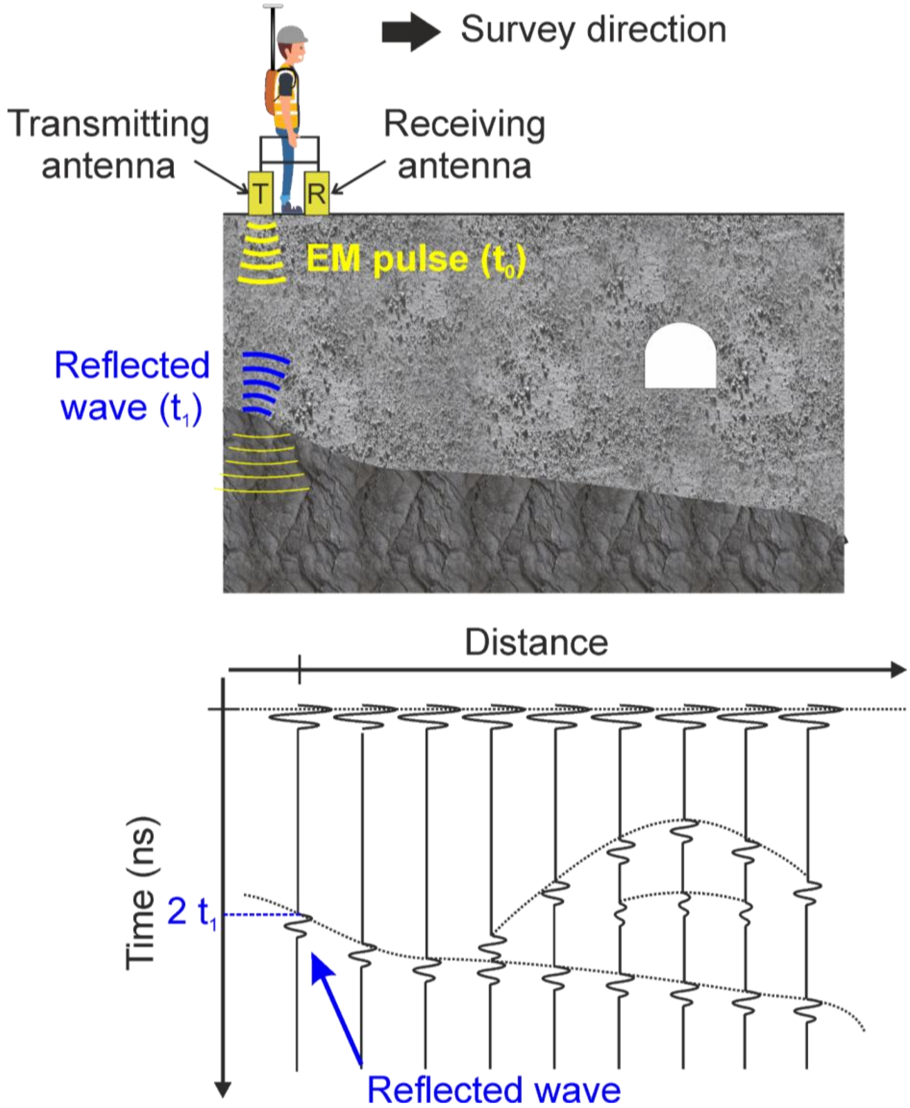

Figure 5: Schematic showing the basic principles of a ground penetration radar (GPR). GPR is commonly deployed as a pair of transceivers (transmitter (T) and receiver (R)), separated by a fixed distance (common offset), which are then moved across the survey area, usually over a regular (geo-located) grid, or with a GPS antenna to provide locational information. The transmitting antenna emits a pulse of EM waves that propagates into the ground until it meets a material with different dielectric properties where part of the signal is reflected to the surface. The amount of reflected energy is dependent on the contrast in electrical properties between the two materials. A part of the source wave continues propagating into the next layer, where it may be reflected at a subsequent interface. At each measurement location a single trace is recorded, showing peaks/troughs (or wiggles) where energy has been detected by the receiver. Arranging the traces in the order they were collected along a profile allows to see what type of feature the wave signal has been returned from. Typically the energy is returned from layers which generally form continuous, but often irregular surfaces, or is returned from discrete, point features, where the returned energy is diffracted and forms a hyperbolic distribution, the peak of which is centred on the feature itself.

Applications to environmental and civil engineering problems include permafrost, groundwater and overburden delineation, and detection of voids, fractures, seepage, and soil and groundwater contamination.

GPR has been widely used for high resolution and high efficiency soil water content measurements at medium scale (Liu et al., 2017) since at these frequencies, there is a direct link between the soil dielectric permeability and its water content (Ling et al., 2016)

A GPR system essentially measures energy reflected or scattered in targets. The amplitudes are recorded as a function of travel time. The system comprises a signal generator, transmitting and receiving antennae, and a receiver that may or may not have recording facilities or hardcopy graphical output. Some advanced systems have an onboard computer that facilitates data processing both while acquiring data in the field, and post-recording. There are three modes of deployment of radar systems: (i) reflection profiling of common offset mode; (ii) wide-angle reflection and refraction (WARR) or common-midpoint (CMP) sounding, and (iii) transillumination or radar tomography. In the reflection profile one or more radar antennae are moved over the ground surface simultaneously, with the measured travel times to radar reflectors being displayed on the vertical axis while the distance the antenna has travelled is shown on the horizontal axis. In the WARR antenna configuration the transmitter is kept at a fixed location and the receiver is towed away at increasing offsets. An alternative is the CMP sounding. In this case, both the transmitter and receiver are moved away from each other so that the midpoint between them stays at a fixed location. The point of reflection on each subsurface reflector does not change, and thus areal consistency at depth is not a requirement. In the transillumination mode of deployment the transmitter and receiver are on opposite sides of the medium under investigation. The radar antennae can be located down boreholes and the radar signals are then propagated from one borehole to the other.

The depth of penetration of a radar pulse depends largely of the electrical conductivity of the investigated material and the frequency of the antenna used. In general, the range of penetration will decrease with increasing conductivity. Moreover, for a given material, lower antenna frequencies increase penetration depth, but resolution is decreased. Therefore, a compromise must be established between the penetration depth and resolution.

5 POTENTIAL METHODS

5.1 GRAVITY TECHNIQUES

Gravity survey is a measurement of the gravitational potential field in a series of different locations. It is an indirect (surface) method that measures the density of subsurface materials where gravity values are directly proportional to the density of the material underneath (Azahar et al., 2018; Murray and Tracey). The objective is to relate the density differences to anomalous gravity changes (**Figure 6**). Any geological condition that results in a variation of density will cause a variation in gravity. The anomaly gravity changes show horizontal density differences of subsurface rocks or materials and could be used to determine the subsurface structure. In engineering and geotechnical applications, gravity surveying is used to locate natural cavities (such as caves, caverns) and man-made subterranean openings, such as abandoned mines, tunnels. Natural cavities may be air-filled, water-filled, soft-sediment filled or partially filled, and it is the density variation between the inner and surrounding materials of the cavity that will help distinguish it. That said, many objects/structures with different volumes and masses at different depths can induce the same gravity anomaly, which complicates the interpretation of the data when no a priori information is available on the area under study (Reynolds 2011). This pitfall can be bypassed by combining gravity data with other data (e.g. from other geophysical methods).

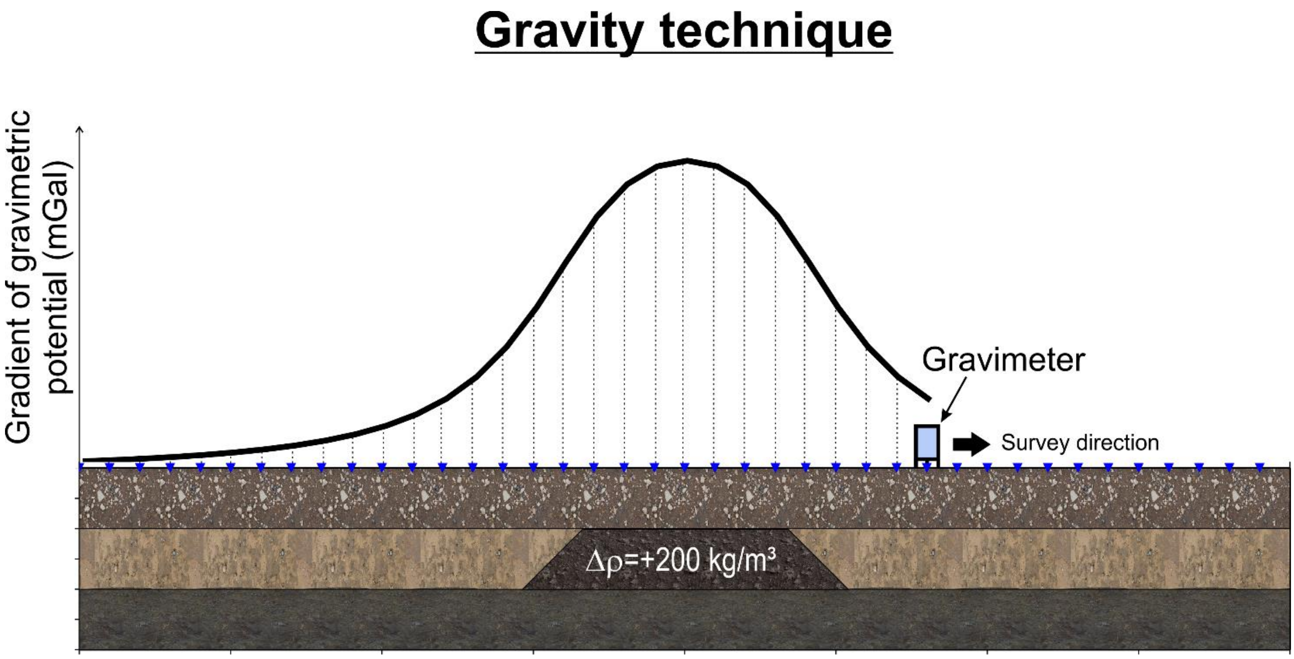

Figure 6: Diagram showing the basic acquisition principles of a gravity survey. Measurements carried out at the earth-surface consist in deploying a gravimeter at different stations along a profile. The measured gravitational field is disturbed in the vicinity of a density anomaly. Data obtained allow to estimate the location of the anomaly.

5.2 MAGNETIC FIELD METHOD

The magnetic method aims at measuring the magnetic field using a magnetometer. As the magnetic field is a vector, it is characterized by an intensity and a direction. During an acquisition, the magnetic field measured by the magnetometer is composed of two components: the terrestrial magnetic field and the magnetic field due to local magnetisation (either induced or remanent). Any deviation of the total magnetic field from the earth's magnetic field is called an anomaly (**Figure 7**). The physical property that determines the magnetisation of a material under an applied magnetic field is the magnetic susceptibility. Measurements can be made in three different ways: 1) measuring the intensity of the total magnetic field, 2) measuring the vertical or horizontal magnetic gradient and 3) estimating the intensity and direction of the total magnetic field. Magnetic gradient measurements are performed by two sensors that are separated by a small distance. The gradient is the difference between the two magnetic fields measured divided by the distance between the sensors. This mode of acquisition focuses on shallow anomalies. In general, magnetic systems are coupled to a GPS for precise positioning. Whenever possible, an acquisition grid is setup over the area to cover with an interline spacing depending on the size of the structure/object to detect. The method is used to locate pipes, cables, drums, unexploded military ordnance or to map boundaries between magnetically contrasted lithologies (Reynols, 2011). The method is relatively inexpensive, easy to deploy (no ground contact required) and fast. However, measurements are sensitive to local disturbances (fences, railways, vehicles, …) and diurnal variations. Although the shape of the magnetic field surface anomaly gives insight on the size and depth of the buried objects, determining these parameters remains a difficult task.

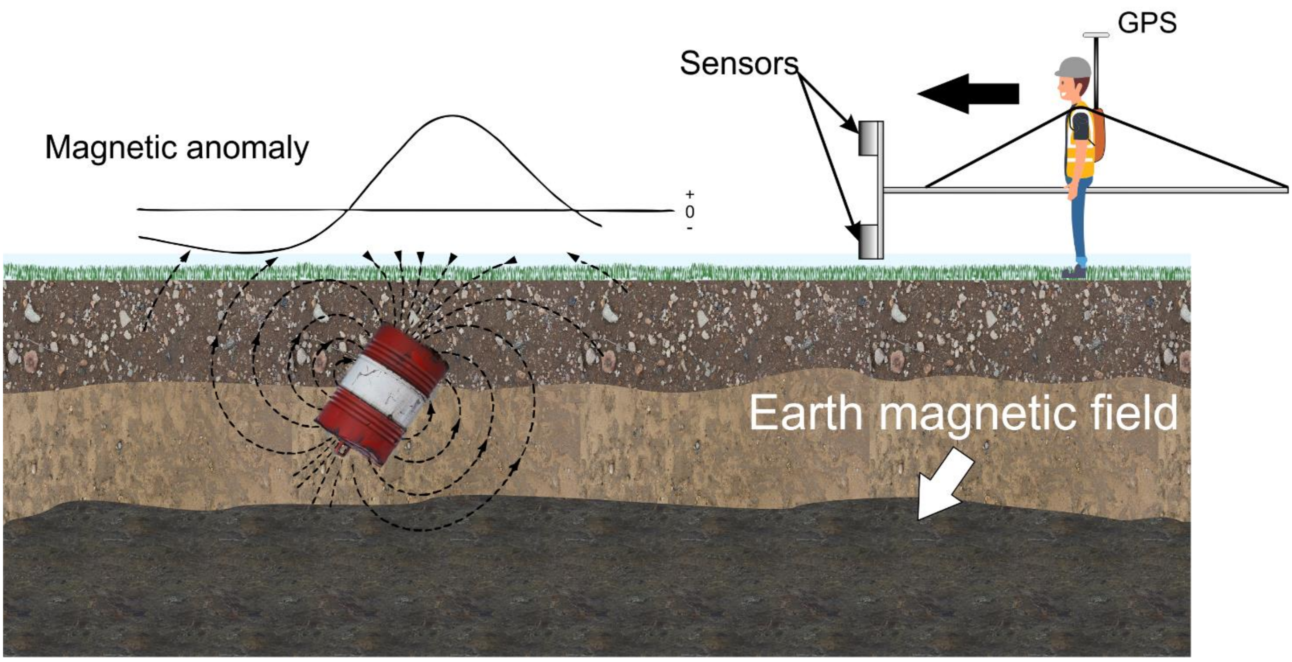

Figure 7: Illustration of a magnetic survey conducted in the vertical magnetic gradient mode. The two sensors measure the total magnetic field composed of the terrestrial magnetic field and the magnetic field due to local magnetisation. Depending on the direction of the latter, the magnetic field measured can be either larger or smaller than the Earth's magnetic field. The upper sensor is less sensitive to shallow magnetic objects than the lower one. Therefore, the difference in the magnetic field amplitudes measured by both sensors allows to highlight shallow objects. The system is moved across the survey area, usually over a regular (geo-located) grid, and/or with a GPS antenna to provide locational information.

5.3 Spontaneous Potential

The spontaneous potential (SP) method, also called self-potential, is a passive method, i.e. differences in natural ground electrical potentials are measured between any two points on the ground surface. The measurement of self-potentials is performed by using two non-polarisable porous-pot electrodes connected to a precision multi-meter with an input impedance greater than 10^8 ohms and capable of measuring to at least 1 mV. Two different electrode configurations can be used, namely the potential gradient and the potential amplitude method. The potential gradient method uses two electrodes, at a fixed separation, between which the potential difference measured is divided by the electrode separation to give a potential gradient (mV/V). The point to which this observation applies is the midpoint between the two electrodes. The potential amplitude method uses a stationary electrode fixed at a base station and measuring the potential difference (in mV) between it and the second one which is moved along the traverse (**Figure 8**).

Self-potentials are generated by several natural sources, although the exact physical processes by which some are caused remain still unclear. One major factor among the various processes thought to be responsible for self-potentials is groundwater. Five main source mechanisms are known: (i) the electrokinetic effect is the electrical response to a fluid movement in a porous medium, (ii) the thermoelectric effect is linked with the diffusion of charge carriers between two areas with different temperatures, (iii) the electro-diffusion or membrane effect is caused by concentration gradient of ions in water; (iv) the redox effect is associated with electron transfers between two different redox zones (typically in ore bodies or contaminant plumes) and (v) the piezo-electric effect is linked to mechanical stress. Historically, the SP technology has been used to detect small scale features such as electrically conductive ore bodies (Rona, 1972). In recent years, the SP method has found an increasing use in geothermal, environmental and engineering applications (Revil and Jardani, 2013) to help locate and delineate sources associated with the movement of thermal fluids and groundwater. Moreover, SP is currently used to investigate a range of contamination events caused by the biodegradation of solid waste – e.g. dump sites (Emujakporue, 2016); organic contaminant transport related to food industry (e.g. olive oil mill wastes – Rani et al., 2019); and metallic plume wastes which contaminate both soil and groundwater (Cui et al., 2017).

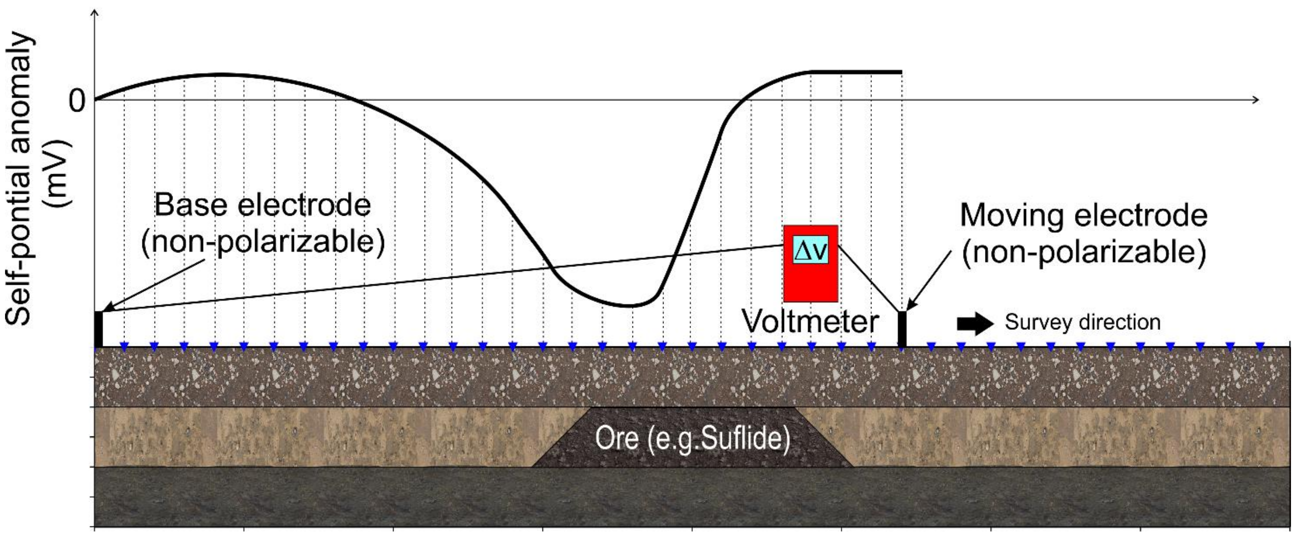

Figure 8: Illustration of the potential amplitude method which uses a stationary electrode fixed at a base station and a second electrode which is moved along the profile. The potential difference (in mV) between both electrodes is

measured with a high input impedance. Different processes may cause the self-potential anomaly. In the example here, the presence of an ore body (redox effect) generates the anomaly.

6 BOREHOLE GEOPHYSICS

Downhole geophysical logging is a set of techniques used to determine the physical properties and distribution of soil and rock surrounding a borehole annulus. These measurements record naturally occurring physical phenomena or, as in the case of the above-mentioned surface techniques, they may use an artificial physical source (*viz* electrical, magnetic, nuclear, acoustic/seismic), to excite the medium and measure the response to the excitation. Borehole geophysics can be used to obtain valuable data including information on geological conditions and *in-situ* physical parameters in drill holes. The amount and benefit of this information is determined by logging suite, borehole conditions, geological parameters, interpreter's experience and application of current technology. The choice of appropriate geophysical methods requires an understanding of the geological environment and the borehole conditions. Very seldom can a geological property be identified from a single geophysical log (BS7022, 1988). As for the surface methods, borehole geophysics usually involves a combination of physics methods to identify each property of interest (e.g. electromagnetic induced methods - to measure conductivity, GPR, acoustic/seismic methods, etc.). However, for its intrinsic nature, borehole geophysical methods allow for the investigation of deeper ground layers.

7 INFRARED SPECTROSCOPY TECHNIQUES

The infrared (IR) electromagnetic spectrum consists of three regions: near infrared (NIR) (750-2500 nm or 1400 – 4000 cm-1), mid-infrared (MIR) (2500-25000 nm or 4000-400 cm^{-1}, and far infrared (25000 – 1000000 nm or 400-10cm^{-1}).The principle of spectroscopy is based on the absorption of energy (light radiation) by substances, which result from fundamental vibrations of molecules that take place in the MIR range. The absorptions measured by NIR spectroscopy correspond mostly to overtones and combinations of fundamental vibrational modes (e.g. stretching and bending) involving C–H, O–H, N–H and S-H chemical bonds (Osborne et al., 1993).

Infrared spectroscopy has been used as a non-destructive technique to evaluate hydrocarbon soil composition for more than 30 years now. It was in the late 1980's when the spectral characteristics of hydrocarbons were documented by Cloutis (1989) for the first time. Organic carbon and other soil properties, such as clay and water content, have direct spectral responses in the NIRS. Heavy metals, however, do not have such direct spectra responses, yet they can be detected by their co-variation with spectrally active components (Stenberg et al. 2010; Todovora et al., 2014).

IR spectroscopic techniques can be used in the laboratory and in the field and provide soil properties information within few millimetres. The laboratory approach has been proved valuable when profiling large sites/areas which yield large number of samples; IR spectroscopic techniques are less expensive and time-consuming compared to analytical techniques such as LC/MS, etc. (Gholizadeh et al., 2020). There are also studies that have used IRS in the field, including remote sensing (e.g. satellite and aerial imaginary), for the determination of physical, chemical and heavy metal content (Angelopolou et al., 2019; Ge et al., 2011; Wang et al., 2018). Details on recent applications of such approaches are provided below.

7.1 Fourier Transform Infrared Spectroscopy

Soil samples can be analysed by Fourier transform infrared (FTIR) spectroscopy using a variety of methods, the most common of which are transmission, diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS), and attenuated total reflectance (ATR) (Margenot et al., 2017). Different modes of acquiring FTIR spectra offer complementary methods for evaluating soil components and processes.

Transmission spectroscopy was the earliest method used to collect FTIR spectra of soil mineral and organic components. Soil extracts (e.g., NaOH-extractable SOM) or suspensions are dried onto infrared (IR) windows (e.g., ZnSe, Ge) prior to analysis, and solid samples such as soils or SOM fractions are ground, mixed, and diluted with potassium bromide (KBr; 0.5–3% sample), pressed into pellets, and desiccated prior to analysis (Margenot et al., 2017). Transmission provides a bulk IR measurement because the beam encounters all parts of the sample, which contrasts with other collection methods such as ATR. Due to the labour of sample preparation and artefacts that can be introduced upon pellet desiccation, transmission spectroscopy is used less frequently today, and less labour-intensive methods have gained favour. One such method is DRIFTS, which entails minimal sample preparation (e.g., drying and grinding).

Soil samples should be uniformly and finely ground (FTIR spectroscopy enables the identification and characterization of metal oxides, a mineral class common in soils that includes oxides, hydroxides, and oxyhydroxides of metals such as iron, aluminium, and manganese. FTIR spectroscopy can be used to characterize and study both crystalline and poorly crystalline metal oxides, thus providing a distinct advantage over XRD, which is primarily limited to crystalline samples. The O-H stretch is highly sensitive to oxide type and properties (e.g., crystallinity, specific conformation of polymorph), and consequently these absorbance bands can be used to identify and determine metal oxide type, structure, and properties.

Goethite (a-FeOOH) and hematite (a-Fe2O3) are two common iron oxides found in soil; other Fe oxides present in soils include ferrihydrite, lepidocrocite, maghemite, magnetite, and schwertmannite. These metal oxides are key indicators of pedogenic processes such as weathering, and strongly influence soil colour and the retention of ions, SOM, and anthropogenic compounds. FTIR has proven to be a key tool for identifying and characterizing these mineral species, particularly for non-crystalline forms that are not readily characterised by other methods. Fe-O and FeO-H absorbances can be used to identify the type of Fe oxide or polymorph and determine crystallinity and cation substitution. Differences in the coordination of Fe with O result in specific Fe-O and FeO-H absorbances at 3400–3000 cm^1, 900–700 cm^1, and <700 cm^1. Absorbance bands of O-H stretching and bending reflect the degree of cation substitution. Band broadening can also reflect decreasing crystallinity.

7.2 VISIBLE-NEAR INFRARED REFLECTANCE SPECTROSCOPY

As opposed to traditional methods (*viz*. microwave mineralization and spectrophotometer measurement via AAS or ICP), which are accurate but expensive and time consuming, vis-NIR reflectance spectroscopy offers a rapid and cost-effective way of estimating heavy metals concentrations (e.g. arsenic (As), cadmium (Cd), copper (Cu), iron (Fe), nickel (Ni), lead (Pb)) in contaminated soil and vegetation (Far and Matifar, 2016; Wang et al., 2018).

Totorova et al. (2012) estimated total Zn, Cu, Pb, Ni and Cd content in soil samples (n=121) from the 0--20 and 20--40 cm layer. They used a NIRQuest 512 spectrophotometer within the range from 900 to 1700 nm and obtained fair PLS regression models for total Cu content with correlation coefficients R=0.92 and RPD=3.9.

The concentration of heavy metals in soil has been determined *in situ* (field) using portable ASD FieldSpec3 meter over the full visible-mid-infrared (MIR) spectrum (350–2500 nm) as reviewed by (Wang et al., 2018). Mohamed et al. (2016) used Vis-NIR spectroscopy to estimate, *in-situ*, the Cr, Mn and Cu concentration in Nile Delta contaminated sites. Using infrared reflectance spectroscopy in bare or mining areas has the advantage of the potential high concentrations of heavy metals, what eases the development of calibration models, and classification between contaminated and non-contaminated. However, the drawback is that in such areas there is a lack of organic matter, which make it difficult to monitor those spectrally indistinctive metals that are correlated with soil organic matter (Wang et al., 2018).

Remote sensing has also been used to investigate heavy metal contamination in soils. Choe et al., (2008) (Reviewed by Melendez-Pastor et al., 2011) derived parameters from spectral variations associated with heavy metals in soils of southeast Spain; then, they used such variation to metals to develop hyperspectral aerial imaging acquired with the HyMAP sensor.

In order to develop robust NIRS calibration models that can be further used as a decision support tool to evaluate the heavy metal composition of multiple sites, a large number of samples need to be considered;

either from the same or different sites with preferably with similar soil composition and hydrocarbon/metal contamination. To overcome this, models have been developed and calibrated using artificially contaminated samples in the laboratory (Reward et al., 2018). Recently, Wijewardane et al. (2020) developed NIRS calibration models based on laboratory-created set samples amounts of hydrocarbons (0-100,000 mg kg^{-1}), which were then applied to field samples. They found that support vector regression calibration models developed by spiking field samples with lab-created contaminated soil samples improved the prediction of TPH (up to R^2 = 88%), TPH concentrations more efficiently and cost effectively compared with generating site-specific calibrations. Another important step is the selection of the chemometrics technique.

8 ADVANTAGES AND LIMITATIONS OF GEOPHYSICAL METHODS

8.1 GEOPHYSICAL METHODS

The advantages of these techniques are that they are fast, low cost, and cover a large area intensively. They offer the best way to capture ground variation which is practically not possible by traditional boreholes measurements. Another advantage is a good correlation between engineering properties and geophysical parameters (Resistivity, Vs, etc.). However, sometimes correlations are not fully explored and established for all types of soils; there might also be physical, chemical or even biological causes to geophysical parameter variations. Furthermore, each technique has its resolution issue and depth limitations. These limitations must be understood to enable the selection of the appropriate techniques (**Table 1**).

All in all, the use of several surface geophysical methods can be combined in order to achieve a more comprehensive study of the site investigated. These techniques are normally validated/complemented with truth measurements from classical methods (such as borehole sampling) to take into account field variations.

Table 1: Strength, Weakness, Opportunities and Threats related to the use of geophysical methods for site investigation.

Strength	Opportunities
- Noninvasive or less invasive - Cost effective - Time effective - Spatial coverage	- Some methods can be used on covered landfill (at least as pre-investigation study) - Reduced risks (gas, drilling, trenching, etc.)

Weakness	Threats
- Indirect measurement (to be interpreted, converted into the useful information) - Lower resolution of surface methods - Non-unique interpretation - Need for trained peoples	- Potentially misleading geological context - Non-uniqueness - Influence of technical infrastructures on the site, applicability in urban areas.

The following cost estimation of the most appropriate geophysical methods for site characterization is based on RAWFILL's experience as it is difficult to find such information in the literature is provided in **Table 2**. Caution is however needed, and readers should bear in mind the proposed values are only indicative as the cost may vary from country to country, from site to site and may also depend on the configuration.

Table 2: Indicative cost of most appropriate geophysical methods for Past Metallurgical Sites and Deposits (PMSD) investigations.

Methods	**Cost in € (excl. taxes)**	**Units**
ERT	1,650 -2,100	1 profile with 64 electrodes
ERT + IP	1,900 – 2,500	1 profile with 64 electrodes
HVNSR	20 - 40	1 measurement point
MASW	1,200 – 2,000	1 profile with 24 geophones
EM	0.013 -0.1	m^2
Magnetometry	0.07 - 0.17	m^2
SP	400 - 830	1 profile with 64 measurement points

8.2 SPECTROSCOPIC METHODS

The main advantages of vis-NIR spectrometry methods is that it is a rapid and cost-effective technology that does not required skilled personnel for their deployment, once the calibration model has been developed and validated. It provides semi quantitative information of soil and plant composition/contamination and when using it under remote sensing settings, it can map considerably large sites. However, the appropriateness of this technology largely depends on the calibration models and validation steps (**Table 3**). Thus, the optimum chemometrics approach (linear *vs.* non-linear calibration modes, or machine learning), a large number of samples, and suitable analytical quantification technique must be selected in order to develop models that can be used for the prediction of heavy metals in soils.

Table 3: Strength, Weakness, Opportunities and Threats related to the use of spectroscopic methods for site investigation.

Strength	**Opportunities**
- Non-invasive or less invasive - Cost effective - Chemical free - *In-situ* rapid technique, no sample preparation needed - No need for trained people	- This technology can be used on soil and plant material - Fine mapping of large sites, e.g. using remote sensing
Weakness	**Threats**
- Need for trained people to develop robust calibration and validation steps, prior to NIRS deployment - Upfront investment - Direct information limited to the upper surface - Sampling and lab measurements needed to obtaining information from deeper soil regions	- Non-accurate/misleading results for low heavy metal content - Semi-quantitative technique

9 SUMMARY

The use of geophysics in geotechnical and geo-environmental site investigations requires a multidisciplinary approach between Civil and Structural Designers, Geotechnical Engineers, Geophysicists and Geologists. If carried out with an in-depth understanding of the applications and limitations of each method, to what the engineers require to assess, then effective results can be obtained. This eventually leads to reduced ground variation risk while saving time and cost. Consequently, it will also increase the quality of the site investigation. Intrusive boreholes must be used in conjunction with the findings. Thus, with appropriate site geophysical scanning, the number of required boreholes is minimised, and the variation risk can also be greatly reduced.

Near infrared spectroscopic techniques can be used to classify or predict the organic and mineral content of soil samples, either on-site (using hand-held equipment) or by acquiring samples to be further analysed in the laboratory. Soil and vegetation composition maps of large and/or inaccessible sites can also be obtained using a remote sensing approach. However, one of the NIRS limitations is that the light can only penetrate the first mm of the soil matrix. To overcome this, soil samples from different depths can be obtained to be further analysed on-site or in the lab. Another major challenge when using NIRS is the need for robust calibration models. However, once these models have been validated, they can be subsequently used in different sites for classification and prediction purposes; therefore, becoming a cost-effective, chemical-free, rapid and non-invasive soil evaluation technique.

10 USEFUL LINKS AND SOURCES OF INFORMATION

A good source of technical information of various methods and their application can be found on vendor websites (e.g. Geoprobe® https://geoprobe.com/, Fugro® https://www.fugro.com/, Advanced Geosciences Inc® https://www.agiusa.com/). The USGS, BGS, BRGM and USEPA also have information on their respective websites, particularly case studies of geophysics applications in support of field remediation trials, as do the websites of the Environmental Security Technology Certification Program (www.estcp.org) and the Federal Remediation Technologies Forum (www.frtr.gov) programmes. RSK also produced an excellent Handbook on Reference for Geophysical Techniques and Applications.

A list of other useful links is provided below

GeoSpectrum Advanced geophysical technics

https://geospectrum.pl/en/applications/ground-studies/

Detailed case studies and applications provided for brownfield sites, landfill sites and contaminated land

https://www.geos.ed.ac.uk/~whaler/environmental_geophysics_handbook_lowres.pdf

The Use of Geophysical Investigation Techniques in the Assessment of Contaminated Land and Groundwater – Technical Bulletin TB5 – 2007 – CL:AIRE

https://www.claire.co.uk/component/phocadownload/category/17-technical-bulletins?download=49:technicalbulletin05

The value of geophysics as a non-intrusive method for site characterisation, Matt Harris (2011) Golder

https://www.wasteminz.org.nz/pubs/the-value-of-geophysics-as-a-non-intrusive-method-for-site-characterisation/

The application of Fourier transform infrared, near infrared and X-ray fluorescence spectroscopy to soil analysis

https://www.spectroscopyeurope.com/system/files/pdf/SE%2028-4-Soil.pdf

Geophysics Handbook – RSK Geophysics

https://www.environmental-geophysics.co.uk/documentation/handbook/handbook.pdf

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