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CL:AIRE technical bulletins describe specific techniques, practices and methodologies currently being employed on sites in the UK within the scope of CL:AIRE technology demonstration and research projects. This bulletin describes the use of geophysical investigation techniques in the assessment of contaminated land and groundwater.

The Use of Geophysical Investigation Techniques in the Assessment of Contaminated Land and Groundwater

INTRODUCTION

Given limited resources and time constraints, site investigations (SI) for contaminated land and groundwater assessments need to generate relevant high quality data in an efficient and cost-effective manner. One important outcome of SI should be sufficient data to construct a robust and representative site conceptual model incorporating site history, 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 remediation strategy may prove less effective than intended.

There is a range of traditional SI methods (e.g. historical studies, test/trial pitting, drilling/coring, monitoring well installation and related sampling), which are familiar to contaminant hydrogeologists. Over the last 15 years, this limited toolbox has been augmented with methods imported from other sub-disciplines in engineering and the earth sciences (particularly oilfield and mineral exploration) and recent technological developments. Where once SI options were limited, and therefore strategies relatively straightforward, practitioners may now choose from a much wider and increasing availability of complementary investigation techniques. Of course, selecting methods for an effective SI programme depends on data needs, budget, and site conditions. However, making best use of relatively new methods (or applying old ones in novel ways) requires an understanding of their capabilities and limitations, both technical and practical. This is particularly true of geophysical SI methods, only very recently embraced by geologists and environmental engineers. This bulletin presents a survey of a representative range of geophysical SI methods, which may be used for contaminated land and groundwater assessments. It includes an analysis of well-established and relatively new geophysical techniques, and illustrates their utility and application for site characterisation using examples from research undertaken by the authors.

All geophysical techniques measure variations in physical properties of the matrix and/or pore water fractions of subsurface materials (e.g. resistivity, conductivity, acoustic velocity, magnetic permeability, density). Changes in these parameters are a reflection of variation in porosity, water permeability, bulk density, mineral type, and/or pore content (gas or liquids) and composition. For example, electrical conductivity or resistivity data can be correlated to porosity, hydraulic conductivity and clay content of porous media, and compressional (P) and shear (S) seismic waves are related to material elastic moduli, and can be correlated to porosity and bulk density. The value in these measurements is how they can be combined through multiple applications to deduce spatial variations in the relevant geological and hydrogeological properties across a range of scales. In turn, an improved understanding of the distribution and transport of contaminants in the subsurface can be gained when these measured properties are integrated into the site conceptual model.

Fig.1: (left) 2-D array deployment of surface resistivity probes for 3-D tomography; (right) photo of probe tied into connecting wire of array.

At contaminated sites, geophysical investigations can be applied at the ground surface (non-invasive), within existing boreholes or cased wells, or during direct push drilling. Each mode of application characterises the relevant property at a different scale and is capable of different resolution – choosing an approach is at least partly a function of the purpose of the investigation. For example, non-invasive techniques are most often used to obtain a site-scale picture of general lithology and shallow subsurface features that can help plan more focussed invasive data collection. Techniques applied in boreholes or cased wells (i.e. rock or existing monitoring wells) and those involving direct push (unconsolidated sediments) sample at a smaller scale, but offer greater resolution. Common to most geophysical methods is the collection of raw electrical or acoustic signal data that must be processed and converted through some form of calibration to allow interpretation. Data processing generally requires specialised software and a certain degree of expertise or experience. There are specialist contractors that offer a complete service encompassing data gathering, processing and interpretation. Also common to all geophysical methods is the need to ensure that the property being characterised is calibrated against a known standard. For example, a sediment core log should be used to calibrate lithology, contaminant concentrations for plume mapping, or residual saturation for non-aqueous phase liquid (NAPL) mapping.

NON-INVASIVE METHODS

Non-invasive geophysical methods (those conducted from the ground surface, including ground penetrating radar, resistivity, seismic reflection and refraction, electromagnetic, magnetic, gravity and microgravity) are ideal when a large area of subsurface needs to be characterised quickly and cheaply. The trade-off for this efficiency is poorer resolution of detail compared with other geophysical and traditional SI approaches. Another criticism levelled at non-invasive geophysics is that data acquisition can be confounded by made ground and associated infrastructure (e.g. buried services) – a frequent situation at many sites in the UK. However, this criticism can be turned to an advantage. Many of these features are an impediment to invasive characterisation techniques; their detection can guide the location of borehole/well installation or direct push investigations. Non-invasive geophysics offers the clear advantage that it is not necessary to drill or dig up sites, particularly useful at active sites where access may be restricted. While some approaches measure ambient or naturally generated energy, most involve transmitting an energy (electrical or acoustic) signal into the subsurface and measuring the amount returning to a receiver or array. The methods relevant to contaminated land investigation are described briefly below, together with some example applications.

Ground Penetrating Radar (GPR)

In simple terms, GPR is analogous to taking an x-ray of the ground. Short pulses of high frequency electromagnetic energy are sent into the ground from a transmitting antenna. This energy propagates according to the electrical properties of the subsurface. When the radiated energy encounters an electrical heterogeneity, part of the incident energy is reflected back to the radar antenna. Reflected signals are amplified, transformed to the audio-frequency range, recorded, and processed. These data can reveal gross heterogeneity in unconsolidated sediments, sediment/rock interfaces, and the water table. Virtually any feature with suitable dielectric properties can be detected and in some cases characterised in some detail. GPR has been used to detect and delineate light NAPL (LNAPL) in soil and at the water table (Daniels et al., 1995), and dense NAPL (DNAPL) in a sandy aquifer (Brewster et al., 1995). Also, buried cables, pipes, drums, and storage tanks can be detected.

The depth of radar penetration depends on the electrical conductivity of the system – conductive elements such as clay layers or metal objects absorb radar energy, reducing the amount returning to the receiver. The radar frequency selected for a particular study is chosen to provide an acceptable compromise between penetration and resolution. High-frequency radar signals produce greater resolution, but are more limited in penetration depth. It has also been noted that repeatability of GPR surveys of unsaturated soils is influenced by moisture content, which needs to be taken into account when comparing time-series results if there has been precipitation on site. The highest quality data is typically achieved where soil moisture content is low.

Resistivity

Like all electrical methods, resistivity data is acquired by inducing a direct current (DC) electrical pulse through the ground from a current electrode and recording voltages at potential electrodes. Various probe deployment configurations have been evaluated (Wenner, pole-pole, dipole-dipole, pole-dipole, square, twin electrode), each with strengths and weaknesses relating to depth and spatial resolution. From the applied current (I) and measured voltage (V), the apparent (bulk or effective) electrical resistivity can be calculated ($R = V/I$) and used to create "pseudo-sections", which are then numerically inverted to resolve subsurface resistivity anomalies. The spacing of probes along a given transect defines the depth of penetration and resolution: close spacing results in shallow penetration but better resolution. The 2-D dipole-dipole method (e.g. Figure 1) has been shown to be particularly good at resolving shallow features.

Dipole-dipole 2-D resistivity pseudo-sections were collected at a methyl tertiary butyl ether (MTBE) site at Vandenberg AFB, California (Figure 2), which proved to be an effective means of defining the gross geology (after calibration to site sediment core) of a large area within a very short period of time, but lacked the resolution necessary to define thin, discrete features that might be important in some situations (e.g. thin sand lenses wherein contaminant plume is confined).

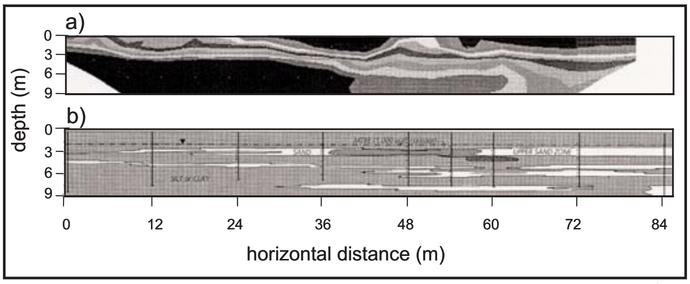

Fig.2: a) 2-D dipole-dipole (4.5 m electrode spacing) electrical resistivity pseudo-section from Vandenberg AFB, CA, showing general stratigraphic features. b) corresponding section constructed from cone penetration test and core log data.

Seismic

Seismic refraction and reflection imaging involves transmitting acoustic impulses from the ground surface to the subsurface – the same as that commonly used in oilfield exploration. When these waves encounter relatively strong contrasts in the subsurface properties (e.g. change in lithology, fractures, metal objects, etc), some of the impulses are reflected back toward the surface where their arrival time and intensity is recorded by geodes. A trial of seismic reflection surveying for DNAPL detection was recently conducted at four Department of Defense sites in the US. While the demonstration results showed that the 3-D seismic surveys were not effective at directly detecting DNAPL, they did determine features (topographic lows, fractures) within which DNAPLs could migrate and accumulate, to provide an indirect interpretation of potential DNAPL distribution.

Electromagnetic

There are two types of electromagnetic (EM) techniques currently used: Time Domain EM, which is used primarily for deep applications, greater than 5 m depth, (and is also the principle behind metal detectors), and Frequency Domain EM, used to map changes in electrical conductivity primarily for the delineation of water bearing units. TDEM typically achieves better resolution than FDEM, but cannot resolve features at depths less than about 5 m. While data outputs are similar to other electrical methods (resistivity and conductivity), better resolution and cost efficiency can often be achieved. The principal advantage EM has over other electrical methods is that the tool does not need to contact the surface – most EM tools can be carried on the users back and data is collected by traversing lines across a site on foot. However, it should be noted that EM cannot penetrate concrete and can be confounded by muddy surface conditions.

Because conductivity variation is detected, TDEM is useful in the delineation of contaminant plumes that have an electrical conductivity different from the background groundwater (e.g. landfill leachates, dissolved organic compounds at high concentrations, dissolved metals). The US Environmental Security Technology Certificate Program (ESTCP) supported two investigations of the use of 3-D EM resistivity to detect and characterise DNAPL sources. These studies showed that EM can differentiate between uncontaminated and contaminated soil, rock and groundwater, but it could not adequately identify where significant DNAPL was located. Another trial at the Baker Wood Creosoting site in Marion, Ohio showed that EM could delineate near-surface soil polycyclic aromatic hydrocarbon contamination.

DOWNHOLE METHODS

There are a number of geophysical methods applied in open (i.e. rock) boreholes and plastic (PVC or HDPE) cased or screened boreholes (steel casing prohibits acoustic and electrical methods). For some, the measuring device (or sonde) is lowered into a borehole, a signal is transmitted into the subsurface and the same device records the returned signal fraction (single hole methods). Alternatively, a signal may be transmitted from one borehole and recording at one or more boreholes some distance away (cross borehole methods). Obviously, these methods are invasive in the sense that a borehole or monitoring well must be created to allow access for the geophysical tool. However, boreholes are usually drilled during the course of a standard site investigation for other purposes (e.g. to provide sediment/rock core samples, groundwater sampling, hydraulic testing), and these can also be used for downhole geophysical investigation. Often, boreholes or monitoring wells may already be installed as part of a previous investigation – making use of these can help direct additional well installation or other SI activities.

Single borehole geophysical methods have a radius of investigation ranging from 0.3 to 1 m, whereas cross-hole methods may reach 10 m or more (Benson, 2006). In general, a signal-emitting device is lowered down a borehole or monitoring well screen and real-time data is acquired via connecting wires and interpreted at the surface by logging software (Figure 3). Some downhole geophysical methods are similar in concept to surface methods (e.g. resistivity and EM), and only differ in the way the technique is used. Other methods are used only downhole because the emitted signal is attenuated so quickly in the subsurface that the detector needs to be as close as possible to the formation being examined. Table 1 is a compilation of some of the more common downhole geophysical methods, how they work and what each measures.

Fig.3: Set-up for downhole geophysical logging at the wellhead.

The single-point resistance method (not included in Table 1) is a hybrid of downhole and surface methods. An electrical signal is transmitted from points along a borehole that are received at short detector probe arrays inserted at the ground surface. Electrical resistance increases with increasing grain size and decreases with increasing borehole diameter, fracture density, and dissolved-solids concentration of the water. The method can resolve lithology, general water quality, and the location of fracture zones. Normal resistivity employs the same principles as surface resistivity, but is oriented vertically in a borehole rather than horizontally across the ground. Potential electrodes are typically spaced 40 cm for short-normal resistivity and 160 cm long-normal resistivity (spacing can also be 20 or 80 cm). Longer electrode spacing "looks" further into the subsurface, but achieves poorer resolution.

Classical interpretation of DC resistivity data assumes intra-stratigraphic homogeneity, and because of its highly diffuse nature, the electrical potential field is smooth. Consequently, conventional resistivity surveys struggle to resolve more subtle, complex and/or small-scale features. Electrical resistivity tomography (ERT) is a relatively new way of conducting traditional resistivity surveys intended to

Table 1: Summary of downhole geophysical methods commonly used in contaminated site investigations

Method	What is Measured	Interpretation
Gamma[1]	Natural gamma radiation emitted by subsurface media surrounding the hole, primarily from potassium-40 and daughter products of the uranium- and thorium-decay series	Identifies clay mineral bearing strata, and is useful in differentiating between sand/ clay or sandstone/shale horizons
Gamma-Gamma[1]	Radioactive source emits gamma particles that are collected at a detector	Measures bulk density of soil or rock
Neutron-Neutron[1]	Radioactive source emits neutron (americium or radium) particles that are collected at a detector	Measures relative moisture content above and porosity below the water table
Normal Resistivity[2]	Electrical resistivity of the borehole environment and surrounding rocks and water as measured by variably spaced potential electrodes on the logging probe	Identifies stratigraphic changes based on clay (electrically conductive) content
Spontaneous Potential[2]	Potential or voltage developed between borehole fluid and the surrounding rock and fluids	Used in the determination of lithology and basic water quality
Ground Penetrating Radar[3]	Returning high frequency electromagnetic energy, ordinarily in cross-borehole format	Indicates lithology and location of NAPLs
Electromagnetic Induction[2]	Electrical conductivity or resistivity of the rocks and water surrounding the borehole	Identifies lithology and zones of electrically conductive contamination, e.g landfill leachate plumes and saltwater intrusions
Fluid Resistivity or Conductivity	Electric resistivity/conductivity of water in the borehole	Reflects differences in dissolved solids concentration in water. Resistivity may also detect NAPLs
Electromagnetic Flowmeter	Voltage generated by water flowing past an electromagnet	Calibrated to groundwater velocity. Vertical profiles in borehole reflect variation in hydraulic conductivity
Thermal Disturbance Flowmeter	Dissipation of a heat pulse from a probe (aka heat pulse flowmeter)	Reflects water velocity flowing past the probe
Caliper	Borehole diameter. Caliper logs are recommended when geophysical logs are collected.	Detects fracturing, washout or caving along the hole, which often affects the response of other geophysical logs
Temperature	Water temperature	Identifies vertical flow between zones of differing hydraulic head penetrated by borehole
Acoustic Televiewer	Magnetically oriented, photographic image of the acoustic reflectivity of the borehole wall	Indicates the depth, strike and dip of fractures and lithologic contacts
Optical Televiewer	Oriented optical colour image of the borehole	Well construction, lithology and fracture network properties, water level, cascading water from above water table, and changes in water quality (chemical precipitates, suspended particles, and gas)

[1] Nuclear method with investigative radius ~0.3 m

[2] Investigative radius ~1 m

[3] Investigative radius up to 10 m, depending on probe spacing. Resolution decreases with increasing spacing. Remaining methods measure within the borehole.

overcome these limitations. Multiple electric current and electric potential data sets are collected in several dimensions. Tomography is the process of joint mathematical inversion of many groups of current source / voltage measurements at as many locations as possible, using an algorithm that can detect more small-scale features. Depending on the geometry of the probe array, high-resolution 2 or 3-D images can be developed.

Electromagnetic induction replaced normal-resistivity logging in the oil industry many years ago, and has begun to do so in hydrogeological applications as well. Induction probes have been designed specifically for smaller diameter holes than resistance probes can access. Induction probes are designed to maximise vertical resolution and depth of investigation and to minimize the effects of the borehole fluid (they can operate in water-, air-, and mud-filled holes and "see" through PVC casing). Major factors that affect induction-log response in sand and gravel aquifers are the concentration of dissolved solids in the groundwater and the silt or clay content of the aquifer.

Often, more than one downhole method is used in the same borehole to provide corroborating evidence and improve interpretation. The results of an investigation at a contaminated site on the Chalk aquifer in southern England provide a case study demonstrating the utility of this approach. Figure 4 shows caliper, gamma, formation resistivity, fluid resistivity and temperature logs collected in the same borehole completed in the fractured Chalk formation, overlain by glacial till and made ground. The borehole was cored and the stratigraphy is also shown in Figure 4. The water table is at approximately 20 m depth (the constant borehole diameter to 19.5 m is temporary casing). The caliper log shows a wide borehole diameter (up to 37 cm) between 19.5 and 22.5 m depth, suggesting the presence of incompetent rock, washout or caving of material caused during drilling. This log was important in the selection of depths for hydraulic testing with straddle packers. The gamma log shows high values from 0 - 6 m, which reflects the presence of made ground and underlying glacial till. Lack of significant variation below 6 m indicates that the Chalk contains very little clay. The formation resistivity log indicates variation in the competence of the Chalk with depth, which is correlated with the presence of a hard ground (compacted low porosity rock) at 29 m and other lithologic features at 35.5 m depth. These markers have been identified in other borehole logs across the site, allowing the 3-D structure of the aquifer to be mapped. The fluid resistivity log shows increasing values with depth below 30 m. The fluid resistivity profile suggests that the groundwater quality and/or hydraulic properties of the aquifer are different above and below the hard ground, that is, the hard ground is acting as a semi-confining layer in the aquifer. The fluid temperature log also supports this interpretation, showing a marked inflection in the vertical profile of groundwater temperature across the hard ground. Downhole acoustic and optical televiewer logs were also collected in boreholes at the same site.

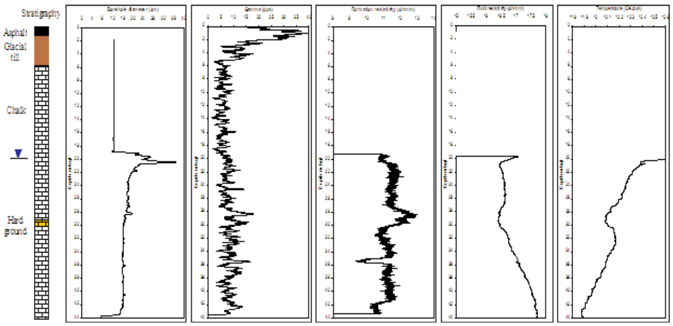

Fig.4: Shown from left to right, caliper, gamma, formation resistivity, fluid resistivity and temperature logs and a stratigraphic section (furthest left) from a site on the Chalk aquifer in the UK.

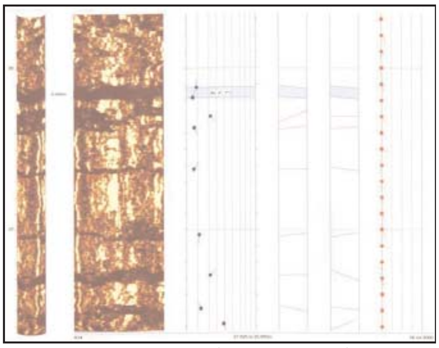

Fig.5: Acoustic televiewer log of a 1.5 m section of the Chalk aquifer showing location of fractures.

Figure 5 shows an unwrapped 360º acoustic image of a 1.5 m section of a borehole, clearly showing the presence of numerous fractures. Figure 6 is an unwrapped 360º optical image of a 30 cm section in the same borehole that shows a single fracture dipping to the north. The fractures are key features controlling contaminant mass transport at this site.

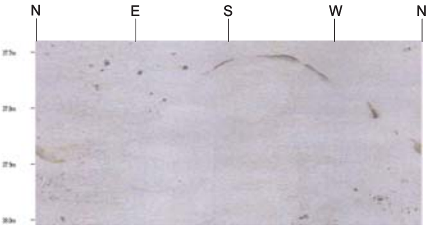

Fig.6: Optical televiewer log of a 30 cm borehole section in the Chalk aquifer shown in Figure 4. The log indicates a single fracture dipping to the north.

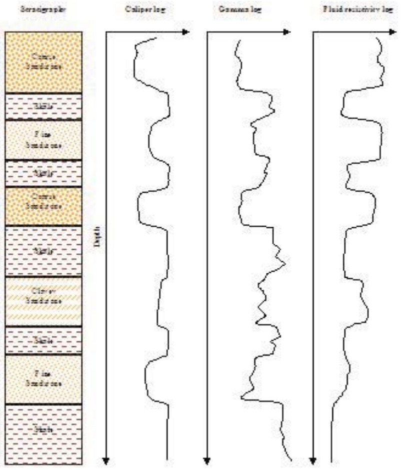

Fig.7: Idealised caliper, gamma, and fluid resistivity logs from a sandstone/shale sequence with different groundwater quality.

In comparison with Figure 4, a set of idealised caliper, gamma and fluid resistivity logs and a stratigraphic log from an interbedded sandstone and shale sequence is presented in Figure 7. High values in the caliper and gamma logs and low values in the fluid resistivity log correspond to horizons that are less susceptible to washout during drilling, contain higher percentages of clay minerals, and porewater containing more dissolved salts (i.e. shale). The decrease in fluid resistivity in the lowest sandstone bed, relative to the upper beds, indicates the presence of more conductive (i.e. saline) water in that horizon. Collectively, these logs can be used to deduce the major differences in lithology, relative thickness of constituent strata and general variation in groundwater quality in this interbedded clastic sequence.

DIRECT PUSH METHODS

For sites underlain by unconsolidated sediments, the most rapid and robust site investigation methods involve direct push rigs that use the weight of the rig and a vibrating hammer to advance a probe into the subsurface. The maximum depth that can be penetrated varies with the diameter of the advancing probe, but 30 m is possible where geology and site conditions allow. Rigs are usually track or truck mounted (Figure 8), making for fast mobilization and allowing access to difficult locations. Probe advance in most unconsolidated material is rapid, roughly 60 - 120 cm/minute. On the order of 200 linear metres of logged borehole per day is possible – making direct push a cost-effective method to collect geophysical data. The range of probe tools has expanded dramatically in recent years to allow characterisation of sediment mechanical properties, lithology, dissolved phase contamination, and NAPL distribution.

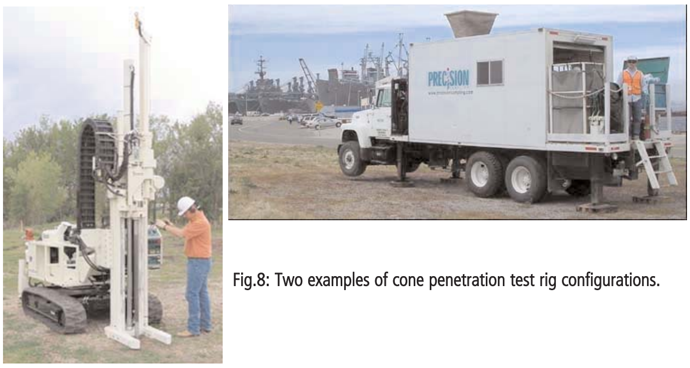

Fig.8: Two examples of cone penetration test rig configurations.

While not a geophysical method *per se*, the cone penetrometer was one of the earliest geotechnical direct push probes, having been introduced over 30 years ago. The tool measures resistance on the tip of the cone and the ratio between friction on the cone tip and outer sleeve as the tool is pushed downwards. The relationship between tip resistance and friction ratio has been calibrated to sediment type, allowing real-time logging of the lithology. While this calibration has been verified at many sites, it still remains good practice to calibrate results to continuous core from a nearby location (direct push rigs also excel at continuous sediment core collection).

Some of the other probe tools that can be advanced using direct push use the same technology as that for downhole and surface methods: electrical resistivity/conductivity, electromagnetic induction, ground penetrating radar, compression wave seismic, and gamma. If enough profiles are collected, the data can be interpreted tomographically in the same way as downhole ERT. An evaluation of tomographic site characterisation was done at the Savannah River Site in South Carolina. A Cone Penetration Test (CPT) rig was used to gather multiple electrical resistance and GPR profiles, which when processed showed the zone of influence of a permeable reactive barrier in 3-D.

Multiple probe types are often advanced in the same push to maximise data acquisition and the cost-effectiveness of the investigation. An example of this is shown in Figure 9, which shows tip resistance (qc), sleeve friction (fs) and pore pressure (u2), and lithology (from core) as a function of depth. By conducting additional profiles in a transect array, geological cross sections can be rapidly generated (see Figure 2).

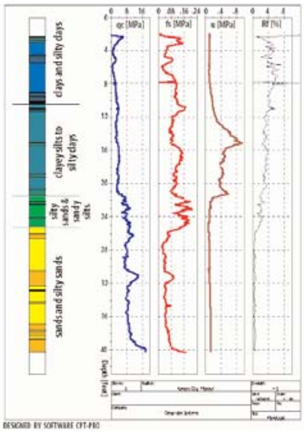

Fig.9: An example of CPT logs showing a stratigraphic log, tip resistance, sleeve friction and pore pressure.

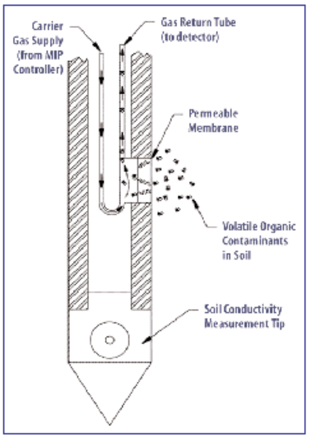

Fig.10: Schematic of the MIP probe tool.

In terms of contaminated site investigation, recent developments are even more promising. Two new probes are currently available that allow indirect detection of dissolved organic contamination and NAPL distribution. The Membrane Interface Probe (MIP) is a permeable membrane device (Figure 10) used to detect dissolved volatile organic contaminants (e.g. benzene, toluene, ethylbenzene and xylene (BTEX) and chlorinated solvents) as it is pushed to depth in soil or other unconsolidated materials. A thin film membrane is impregnated into the stainless steel screen on the probe face. This membrane is heated to 100-120ºC, which leads to quick diffusion of volatile contaminants across the membrane into a carrier gas stream that transfers the contaminant to a detector at the surface (e.g. photoionization detector (PID), flame ionization detector (FID), or other). Coupled with a CPT probe, the location of contaminants can be correlated to lithology in real time.

Figure 11 is a direct push log of MIP and electrical conductivity response collected at an unconsolidated site contaminated with chlorinated solvents. In this example, the three analytical detectors used (FID, PID and Dry Electrolytic Conductivity Detector (DELCD)) indicate hydrogen/carbon bonds, carbon-carbon double bonds and halogens, respectively. The increases in all three signals between 4.75 and 7.5 m indicate the presence of high concentrations of dissolved chlorinated solvents, suggesting the presence of NAPL.

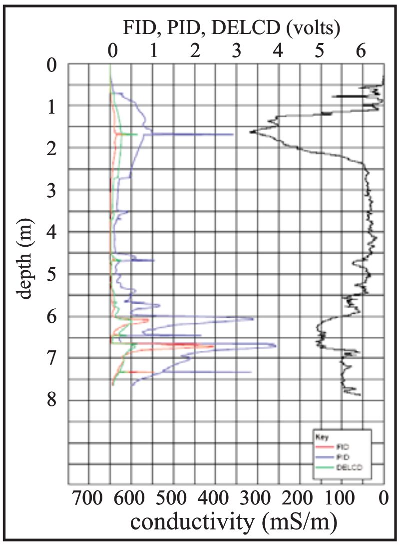

Fig.11: Example of a MIP log from a site contaminated with chlorinated solvents, showing FID, PID and DELCD detector response.

The Laser Induced Fluorimetry probe (sometimes referred to as the Rapid Optical Screening Technique – ROST) makes use of the fact that some organic liquids (or mixtures) will fluoresce when exposed to ultraviolet light. The probe uses a wavelength-tuneable ultraviolet laser source coupled with an optical detector to measure fluorescence via optical fibres, a technique known as laser-induced fluorescence spectroscopy (LIF). The measurement is made through a sapphire window on the probe as it is pushed into the ground. This allows real-time detection of any crude oil derivatives such as petrol, diesel, jet fuel, oils and coal tars. Because laser wavelength is tuneable, a certain degree of compound speciation is possible. However, the most promising use of this probe is for rapid delineation of source zones for subsurface contamination.

Resources

A good source of technical information of various methods and their application can be found on vendor websites (e.g. Geoprobe®, Fugro®, Advanced Geosciences, Inc®, Geo-Services Intl (UK)). The USGS 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 in the US. Many academic research groups host useful basic information on their websites.

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