APPLICATIONS OF ELECTRICAL AND ELECTROMAGNETIC METHODS FOR ENVIRONMENTAL AND GEOTECHNICAL INVESTIGATIONS

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Abstract. Electrical and electromagnetic methods are powerful tools in environmental and geotechnical investigations. Techniques developed for deeper applications, such as mining, geothermal and crustal studies, are scaled for shallow targets by moving to higher frequencies, earlier decay times and/or smaller array configurations. Another extremely important factor is dense station spacing, to reduce spatial aliasing, and high quality data to resolve small features. Hence, new instruments are concerned with making continuous or dense measurements with high precision, and interpretational methods fast enough to handle large datasets quickly. Continuously measuring electrical and time-domain electromagnetic systems have been developed for geological mapping in hydrological investigations with one-dimensional inversion routines that are rapid and robust. At a smaller scale an electrical system is used for archaeology studies with excellent results. Working to and above the upper limits of the quasi-static approximation, a very early time electromagnetic system is proving successful at mapping subsurface infrastructure in areas of conductive, clay cover, where ground penetrating radar is ineffective. Induced polarization (IP) and resistivity systems that employ multiplexing techniques, while not continuously measuring, allow for relatively rapid production rates and dense sampling for applications ranging from landfill and contaminant characterization studies, to verifying the integrity of engineered subsurface structures and monitoring infiltration in the vadose zone.

Keywords: aquifer mapping, archaeology, contamination, electrical, electromagnetic, environmental, geotechnical, hydrological investigation, induced polarization, site characterization

1. Introduction

Merely scaling a deep investigation tool with respect to frequency, decay time or array configuration to adapt it to near-surface investigations is insufficient. It is also important to increase the spatial sampling density and thus reduce aliasing when looking for spatial variations in near-surface geology. As a result electrical resistivity (ER) and electromagnetic (EM) instruments have been developed that make continuous measurements, similar to those in ground penetrating radar (GPR). Traditional discrete measurement systems have been modified with multiplexing large electrode arrays so that large, dense datasets can be collected more rapidly, thereby making them economic to use for routine investigations.

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The key aspects to densely sampled data include the obvious factors such as enhanced resolution of the subsurface in addition to the ability to identify noise and multi-dimensional effects, and reduced spatially aliasing of the data, all of which are important for inversion schemes.

Some of the most significant achievements have been accomplished by researchers focusing on a specific problem, instead of developing generic tools without thought to an optimal application. An excellent example of a transfer of technology from one application to another is the rapid TEM inversion by Christensen (2000) developed to interpret high-density surface data acquired for groundwater characterization. This one-dimensional (1D) inversion code was used later on an airborne electromagnetic (AEM) mining survey where over 700 000 soundings were inverted in roughly 4 hours (Poulsen et al., 1999).

As shown in many case histories and methodology studies reported in this review (Supper et al., 1999; Vanhalla, 1999) induced polarization (IP) is one of the most powerful techniques for environmental application. In 1974 Angoran et al. (1974) showed that IP is a powerful method for landfill characterization. After many years using GPR, conductivity meters and resistivity, IP appears to be the most accurate tool of the trade (Carlson et al., 1999).

This paper builds on the comprehensive tutorials and reviews by Nobes (1996) and Tezkan (1999). Therefore I emphasize new and innovative applications of traditional geophysical techniques and highlight recent achievements in instrumentation and data processing. The reviewed literature mainly cites conference proceedings since 1998.

2. Archaeology

Archaeological investigations are some of the most aesthetic applications of near-surface geophysics. Successfully integrated approaches include GPR, magnetics, conductivity mapping and/or geoelectric methods. Hesse et al. (1998) investigated the location of the Heptastadium in Alexandria, Egypt. Komatina and Timotijevic (1999) explored the Prevlaka Island, Montenegro, Yugoslavia. Cardarelli et al. (2000) conducted a geophysical survey on the vault of "Scarsella" of the S. Giovanni Baptistery, Italy. And El-Behiry (2000) used geophysical surveys to delineate buried tombs and identify their environmental status in Egypt. These and other studies (Panissod et al., 1998; Patella and Mauriello, 1998) have repeatedly shown that geoelectric methods, including ER and IP, are powerful tools for subsurface imaging. Experiments with the spectral IP technique are not as successful (Weller et al., 2000). As with other near-surface applications proper spatial sampling is a critical factor for accurately imaging archaeological sites. Panissod et al. (1998) have developed a series of systems for high spatial sampling, including mobile pole-pole, towed, electric and electrostatic multi-pole systems.

The mobile, pole-pole system, pulled by a walking operator, is shown Figure 1a. Electrical contact with the ground is made with the spiked electrode wheels. The data shown in Figure 1b were collected at Wroxeter, Shropshire, England. Wroxeter is a large Roman-British city (Viroconium Cornoviorum) that constitutes an archeological reserve, which is part of the Wroxeter Hinterland Project, University of Birmingham. The electrode wheels have a separation of 1 m; each constitutes a current and potential pole. A long thin wire at a distance of at least 50-m connects the two other poles. The investigation depth of this array is slightly better than that of a 1 m/side square array. The sampling step is 0.1 m along profiles and 1 m between profiles. The Wroxeter results were resampled at a 1-m step with median filtering. The survey area of an uncultivated pasture covered a 4 hectare (ha) area and the data were acquired at a rate of 5 hours/ha.

The Wroxeter survey results exhibit a very good map of the ancient city: three major streets and two large adjacent buildings together with many small features are clearly evident in black. These structures are made of calcareous stone that are more resistive than the surrounding sandy soil. The conductive, white lines correspond to backfilled gas pipeline trenches, and the bright, conductive spots correspond to farming artifacts.

3. Contamination

Contamination of the subsurface can take place in many ways: pollution of groundwater or soil through direct contamination, saltwater intrusion, or leakage from buried waste, landfill or even from a cemetery (Bastianon et al., 2000). Mapping of protective, clay layers is discussed in the hydrology section below. Delineation of saltwater intrusion, whether from sea water or made-man sources, is an ideal problem for EM and electrical methods, and they have been used successfully for years. Recent studies are concerned with detailed characterization such as temporal variations of flow direction, seepage velocities and transport mechanisms (Lipfert et al., 1999); temporal saltwater effects on porous sands through tidal cycles (Sandberg and Slater, 1999); salt transport processes (Slater and Sandberg, 1999); the salinity transition zone beneath ground water lenses (Kauahikaua, 1999); and the spatial distribution of brines beneath the Sea of Galilee (Goldman et al., 1999).

The particularly difficult problems of detection of hydrocarbon and non-aqueous phase liquids (NAPL) are being approached through different paths. Geophysics are used to delineate confining geological structures that are controlling the migration of the contamination. Laboratory measurements are made to understand the physical response that might be observed in the field. Volkov et al. (2000) examined the effect of oil and oil derivatives on the electrical properties of soils, and found that the main process controlling the changes in resistivity and chargeability is water evaporation and related changes in mineralization.

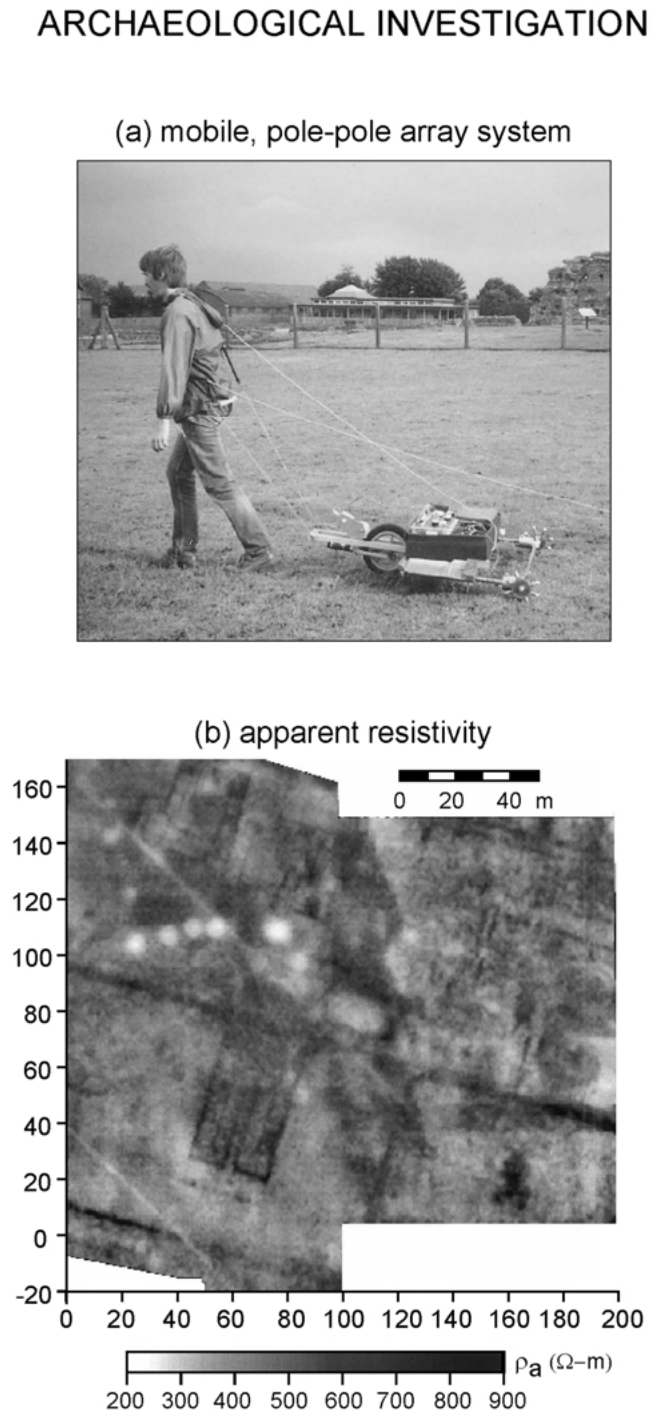

Figure 1. (a) The mobile, pole-pole array resistivity system pulled by a walking human operator. (b) The Wroxeter (Shropshire, England) apparent resistivity map acquired with the mobile pole-pole array with inner electrode spacings of 1-m (Panissod et al., 1998).

GPR has been the tool most commonly used for hydrocarbon and NAPL detection, but with limited success, and researchers continue to look for breakthroughs with inductive and galvanic systems. Carcione and Seriana (1999) have developed an electromagnetic modeling tool for the detection of hydrocarbons in the subsoil. Morgan et al. (1999) have imaged a jet fuel plume of benzene and ethyl dibromide using time-domain IP. A dipole-dipole array was used at four decay times; chargeability and spectral chargeability were able to delineate general plume boundaries. Considering the difficulty of imaging a resistive target in a complex geological framework, an integrated approach is probably best. Godio and Morelli (1999) used a conductivity meter in a reconnaissance survey to plan a GPR survey. GPR was then used and followed up with an electrical resistance tomography (ERT) survey to detect and define the lateral distribution of hydrocarbon pollution. The geophysical responses were then calibrated with ground truth from drill holes.

Geophysics has been much more successful at monitoring the remediation of organic contaminates than direct detection. Newmark et al. (1999) monitored the physical and chemical changes of an in situ thermal remediation process. The ERT method was used to monitor the steam front in conjunction with chemical sampling that was used to determine the level of contaminant in the ground. Vichabian and Morgan (1999) used the self potential (SP) method to monitor an air sparging procedure, which is used to enhance the oxygen level in the soil, and soil vapor extraction to remediate a jet fuel spill at the Massachusetts Military Reservation, USA. Although mainly qualitative, the SP response was converted to partial pressures of oxygen with realistic results. Microbial remediation techniques are very popular. Werkema et al. (2000) used vertical resistivity probes to monitor distribution of microbial abundances at a LNAPL spill site. They inferred that resistivity measurements could provide a measure of the ongoing biogeochemical process. A peak in total heterotrophic microorganisms and in oil degrading microorganisms coincided with a broad apparent resistivity low.

Mining and related activities have often produced by-products that pollute the environment. Hence, it is not surprising that new geophysical systems have come out of the mining community to characterize these related pollutants. Multi-electrode geoelectric profiling was used to explore the spreading of salt contamination and to design a protection scheme at a uranium processing slurry storage in Hungary (Berta et al., 2000). Lahti et al. (2000) are undertaking a pilot project in eastern Germany to assess AEM method in mapping contaminated soil. Kulessa et al. (2000) are working on a magneto electrical system for imaging of subsurface pollution.

Traditional instrumentation is used to ascertain the viability of a method, and developments in technology are making proven methodologies efficient. Buselli and Lu (1999, 2000) and Lu et al. (2000) have developed a 64 channel system to simultaneously record the response of many electrodes using both resistivity and the IP methods. At the Ranger minesite, discussed below, they could collect 30 Schlumberger soundings with a station spacing of 10 m in roughly half a day.

The system also can be used to acquire high quality SP data. SP data are usually very noisy due to time varying telluric currents at frequencies less than 1 Hz; this noise can be eliminated through simultaneous measurements of the response from a number of electrodes averaged over an extended time (Lu et al., 2000).

Figure 2 shows (a) SP data, (b) a two-dimensional (2D) inverted chargeability section (c) a 2D inverted resistivity section and (d) changes in IP chargeability from the working Ranger uranium mine site, Northern Territory, Australia (Buselli and Lu, 1999, 2000; Lu et al., 2000). Thirty receiver electrodes were used to set up a 5 by 6 grid north of a tailings dam where seepage was identified by geochemical data. SP data were acquired several times in one day and over a three-day period. The pattern of the SP response is coincident with the known pattern of seepage and is inferred to indicate the degree of groundwater contamination.

Resistivity and IP measurements, acquired along a profile line intersecting the SP grid, were made in different seasons (beginning of the wet season and middle of the dry season) to test the ability to monitor changes in the hydrogeological conditions. Major features, seen in Figures 2b and 2c, are reproducible. Profiles showing the change of chargeability of the top 10 m of the ground between the December 1998 and July 1999 surveys are seen in Figure 2d. The changes are due mainly to irrigation carried out during the second survey and correspond to changes in ion concentration in the groundwater. A clear trend of increasing chargeability is seen towards Fault 2a (8700 E) at the eastern end of the line.

4. Engineered Structures

This category of applications broadly includes the use of geophysics for investigation of man-made structures such as subsurface barrier verification, pipeline characterization, and mapping of subsurface infrastructure. Engineered structures often require non- destructive imaging and/or monitoring. The geophysical community, using both traditional and innovative approaches has taken on a variety of problems. Many are more environmental than geotechnical in nature because the target of the survey is the remains of a structure that may have environmental implications.

4.1. Infrastructure

Sometimes important questions can be answered with a very simple survey. Hobbs and Vickery (1998) and Rogers et al. (2000) used the Geonics EM-31 instrument (McNeill, 1980) with excellent results. The first survey was performed over land formerly used as oil distribution terminals by Texaco and Shell in Edinburgh, Scotland. In the 1980s the site was supposedly cleared and is now vegetated with only some pipes showing above the surface. After surveying a test site where the pipes were visible, 13274 in-phase and quadrature measurements were taken on

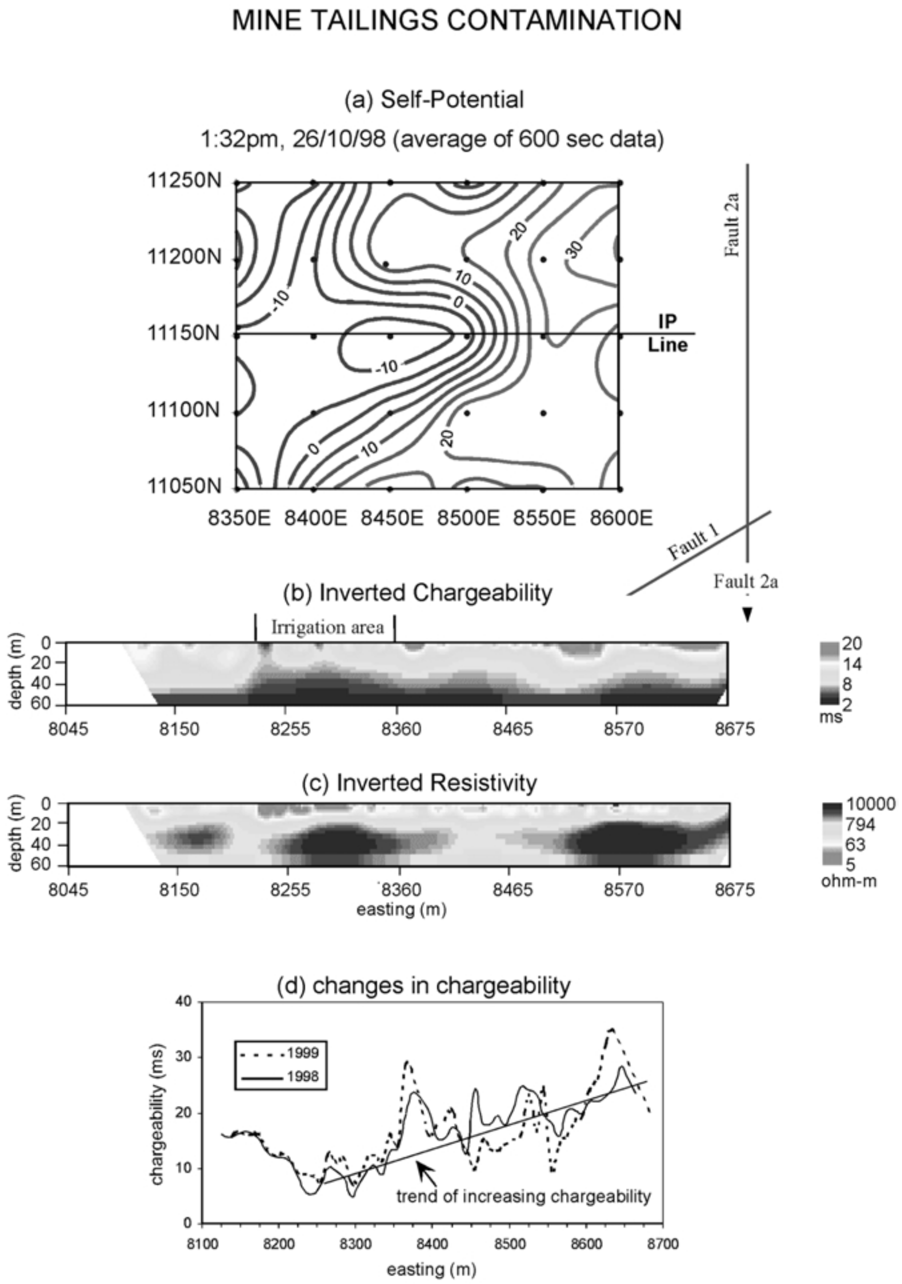

Figure 2. (a) Self potential data, (b) 2D inverted chargeability section, (c) 2D inverted resistivity section, and (d) changes in chargeability from the Ranger uranium minesite, Northern Territory, Australia. Data acquired with the CSIRO 64 channel system. (Buselli and Lu, 1999, 2000; Lu et al., 2000).

a 2 × 2 m grid spacing with the boom in both directions. The oil distribution pipeline network at a depth of roughly 1 m was clearly delineated in the quadrature response and further enhanced by use of second horizontal derivative processing. The existence of the remaining pipeline network was a surprise to the contractors.

The survey of Rogers et al. (2000) was performed in Los Angeles, California, USA, where an abandoned petroleum storage tank was under investigation. The bowl-shaped tank, built in the 1920s, was 600 ft (183 m) in diameter, approximately 25 ft (7.6 m) deep and held roughly 42 million gallons (159 million liters). Originally a buried, open-top, concrete-lined reservoir, the tank was backfilled. Later there was concern about the possibility of leakage and migration of contaminates. Both an EM-31 and a magnetic survey were performed. The outline of the tank was clearly delineated in all datasets (magnetics, quadrature and in-phase); the EM data may have detected the continuity of the tank.

In contrast to the simple and traditional EM-31 surveys, an innovative Very Early Time EM (VETEM) survey was performed to delineate the remains of a munitions foundry in the USA (Wright et al., 2000). The VETEM system was developed to work in the range between inductive EM and GPR for areas where GPR is problematic, such as in conductive terrain. The Denver Federal Center near Denver, Colorado, USA, was a center for the production of small arms and artillery ammunition during World War II. After the war the foundry was removed but remaining subsurface parts of the building remained under a clayey loam soil. The conductive cover of 3–15 ohm-m made GPR unfavorable for delineating the subsurface objects, so a VETEM survey was performed (Wright et al., 2000).

The VETEM system is a loop-loop instrument operating at the upper induction limit, defined as the transition zone from diffusion to wave phenomena, from 0–16000 nanoseconds (ns). The system, pulled by an all-terrain vehicle (ATV), is shown in Figure 3a, at a rate of 25 cm/s resulting in a spatial data interval of 25 cm along line. Line spacing was 1 m. Figure 3b is an amplitude, shaded-relief, time-slice image at a time of 3300 ns, using 2-m spaced, perpendicular loop antennas. Major features of tanks and walls, at a shallow depth of roughly 1 m, are noted. Correlation with a magnetic survey is not high, indicating that many of these features are not ferrometallic.

A variety of EM and electrical methods have been used to directly image and monitor engineered structures. Payne and Corwin (1999) used the SP method to detect changes in the seepage flows through embankment dams. SP is sensitive to streaming potential caused by groundwater flow, and although it is not a very quantitative technique, it has been successful for monitoring seepage with time. Efimova (1999) evaluated the concrete for a road tunnel construction before and after injection using an integrated scheme of GPR and electrical resistivity methods. A geoelectric survey was used in conjunction with a geotechnical investigation to determine the original core of Fundão Island, located in Guanabara Bay near Rio de Janeiro, Brazil (da Rocha at al., 1998). The island is the result of an artificial embankment of a former small archipelago built in the early 1950s. At the other end of

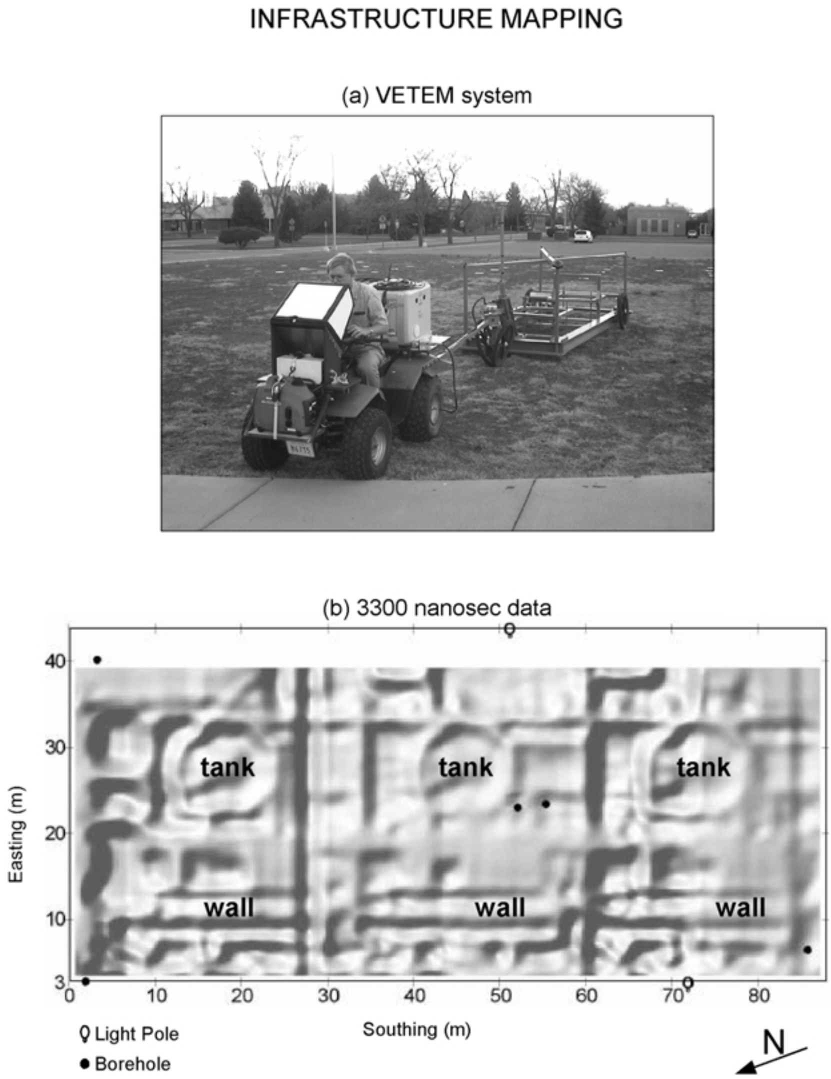

Figure 3. (a) The Very Early TEM (VETEM) system pulled by an all terrain vehicle. (b) Amplitude shaded relief, time-slice image at a time of 3300 ns, using 2-m perpendicular loop antennas, over a former munitions foundry. Images of tanks and walls are noted (Wright et al., 2000).

the spatial scale, Gibson et al. (1999) used time domain reflectometery (TDR) and resistivity logging to examine the integrity of seals placed in exploratory boreholes.

4.2. Subsurface barriers

The primary purpose of subsurface barriers, whether geologic or engineered, is to stop or divert the flow of either water and/or contamination. For a barrier to be used reliably however, a verification and monitoring program is necessary. Geophysics is becoming an important component of verification methodology in both the USA and Europe. In Germany, Ullrich and Heydecke (1998) used 2D inversion of ERT data to detect a geological barrier of a waste deposit site within an unsaturated, disturbed till complex. Mihalffy et al. (2000) used ER soundings to locate a natural barrier in the subsurface that separated nitrate contamination from the Danube River in Hungary. In Sweden, Bernstone et al., (1999) developed a wire net sensor system, based on the ABEM Lund Imaging System, for permanent installation to locate leaks through environmental barriers built from clayey soils and artificial liners. In Italy, Morelli et al. (1999) used ERT to image an earth embankment along one of the effluents of the Po River and to monitor the continuity of an impermeable diaphragm emplaced to prevent/minimize hydrological piping in the embankment.

In the USA, Pellerin et al. (1998) and Daily and Ramirez (2000) have shown that ERT and GPR can be used to verify the integrity of a subsurface concrete grout barrier. ERT was particularly successfully at monitoring a salt-water flood of a thin-walled grout cell emplaced in the vadose zone at the Dover National Test Site, Dover Air Force Base, Dover, Delaware, USA. The vertical walls of the cell were emplaced with a high pressure jetting technique; the floor of the cell was a thick, marine clay layer. The cell was excavated to provide ground truth for the flaw detected by ERT and GPR. Figure 4a shows the excavated barrier and Figure 4b the flaw marked with white spray paint. Vertical electrode arrays (VEA) ringed the barrier and one in the center as shown in white in the series of plots in Figure 4c. The barrier is also outlined in white. The thick, black ellipse depicts the 35% resistivity change isocontour. The upper left-hand plot is the deepest depth section (5.4-m), and the lower right is the most shallow (0.6-m). Within 4 hours the 35% isocontour, defining the salt water, had escaped the barrier at intermediate depths of 3.6 to 2.4 m.

4.3. Utilities

Pipeline detection and the use of EM methods are a natural combination, but not always trivial in practice. There are many types of pipelines, not all are conductive, and there are often cultural problems in urban areas. There is also the constraint that engineers involved with locating and identifying a pipeline require a 100% success rate. Bobachev et al. (1998), McCann and Fenning (2000), and Rozimant and Gajdos (2000) discuss many of the problems and solutions associated with pipeline delineation.

EM fields can be naturally induced in pipeline and powerline grids increasing the soil to pipe line voltage, which can disrupt the infrastructure. The Finnish Meteorological Institute (Pirjola et al., 1999, 2000; Pulkkinen et al., 2000; Viljanen et al., 1999) has been studying geomagnetically induced currents in pipeline and powerline grids for many years. Currents of more than 5 A can be induced during strong auroral activity that can severely degrade a pipeline or hamper cathodic protection.

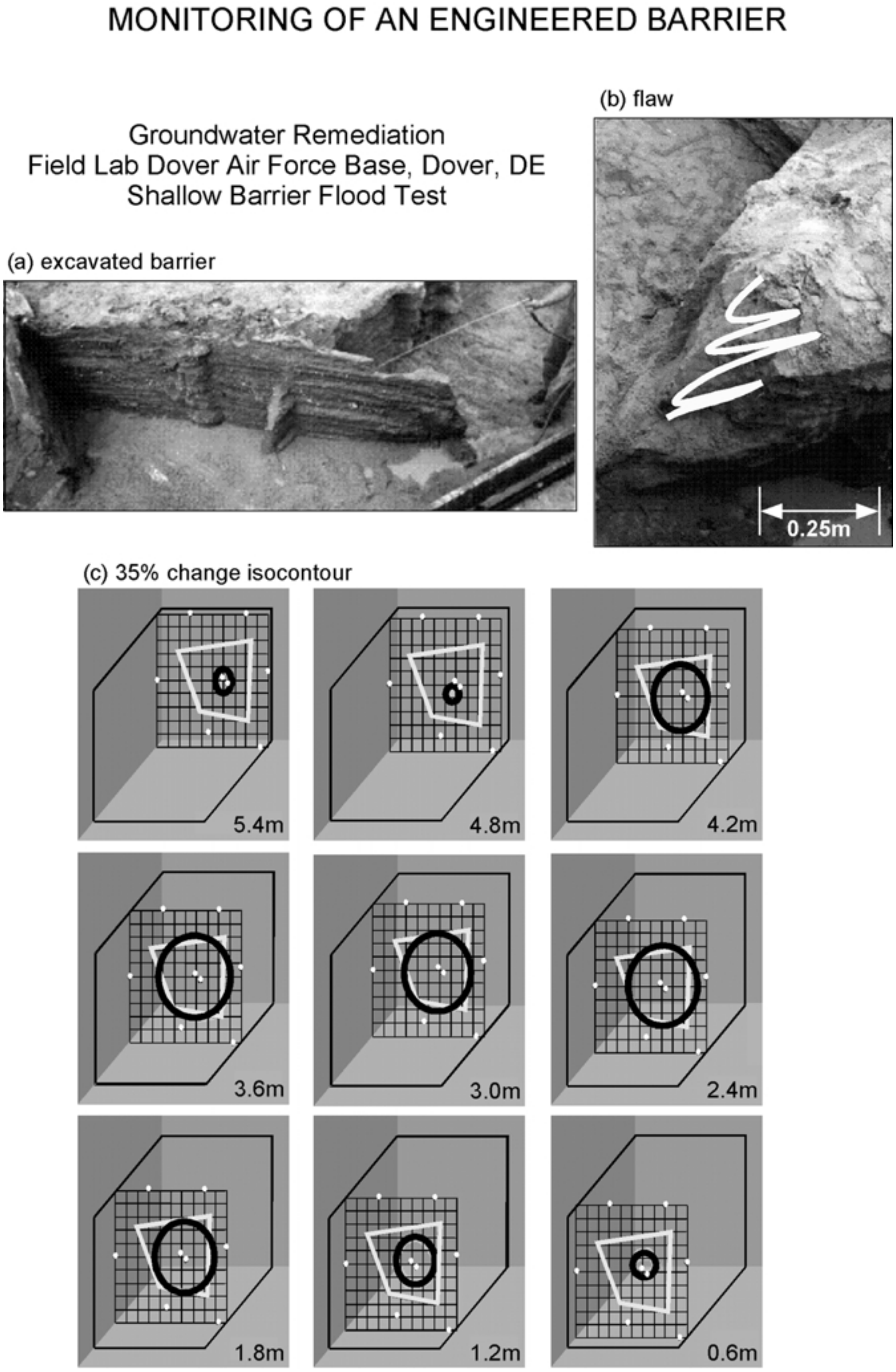

Figure 4. The excavated concrete grout barrier showing (a) a thin-wall and (b) a flaw spray painted white. (c) Electrical Resistance Tomography (ERT) results of the monitoring of a salt water flood, shown in depth slices, approximately 3 hours after initiation. White dots show the position of the vertical electrode arrays and the closed white lines depict the location of the barrier. The black ellipse delineates the 35% resistivity change isocontour representing the salt water front. The flaw is evident in depth slices 2.4 to 3.6-m (Daily and Ramirez, 2000).

5. Hydrological Investigations

Hydrological investigations are one of the most important applications of electrical and electromagnetic methods in environmental geophysics. These investigations range from geological mapping of formations that protect an aquifer, to estimating volume extent and internal structure of aquifers, to mapping the infiltration of the vadose zone, and contamination of the groundwater.

5.1. AQUIFER MAPPING

Water is essential to human life, and the use of geophysics in determining the quantity and quality of groundwater has been pursued worldwide (Goldman, 2000). Resistivity, IP and EM methods have been applied to groundwater investigations of the eastern margin in the Parnaíba Basin, Brazil (Meju et al., 1999), the Karoo aquifer at Nyamandhlovu, Zimbabwe (Gwaze et al., 2000); the Leon-Chinandega Plains, Central Nicaragua (Corriols et al., 2000); Santo Domingo, Nicaragua (Mendoza et al., 2000); Monclova, Mexico (Miele et al., 2000), the Chihuahua Desert, Mexico (Maillol et al., 2000), the USA – Arizona (Wynn et al., 2000), Nevada (Farrell et al., 2000), New York (Peavy and Valentino, 1999), Texas (Paine et al., 2000), and in Denmark (Sørensen and Søndergaard, 1999).

The hydrogeophysics group at Århus University, Denmark has made many advances in the continuous mapping of the subsurface for aquifer characterization. This has been accomplished using the pulled-array, continuous electrical sounding (PACES) and the pulled-array time-domain electromagnetic (PATEM) methods (Sørensen, 1996; Christensen and Sørensen, 1998; Sørensen et al., 2000), and corresponding rapid, robust inversion techniques (Christensen, 1997; Effersø et al, 1999; Christensen, 2001; Auken et al., 2000; Møller et al., 2000). The Danish hydrological problem can be divided into three parts: delineation, vulnerability and internal structure of an aquifer to depths of 250 m of Quaternary sediments. An aquifer is delineated by determining the depth to a conducting, bounding layer – clay or seawater – with the PATEM system. The vulnerability of the aquifer is mapped with the PACES system by determining whether there exists a protective clay cover or an infiltration window of sand or gravel.

The PACES system uses a small tractor that pulls electrode arrays with 8 electrode configurations. The electrodes are heavy stainless steel cylinders galvanically coupled to damp ground. Coupling with the method would be problematic in a desert environment. Figure 5 shows (a) the PACES system in operation, (b) raw and filtered profile data, (c) stitched together single-site 1D inversion results, and (d) a 1D Laterally Constrained Inverted (LCI) section of the top 20 m. The LCI algorithm constrains the neighboring single-site 1D inverse models so that the 2D section varies smoothly (Auken et al., 2000). Clay, sand and gravel, corresponding to resistivity values, are noted in the LCI section of Figure 5d.

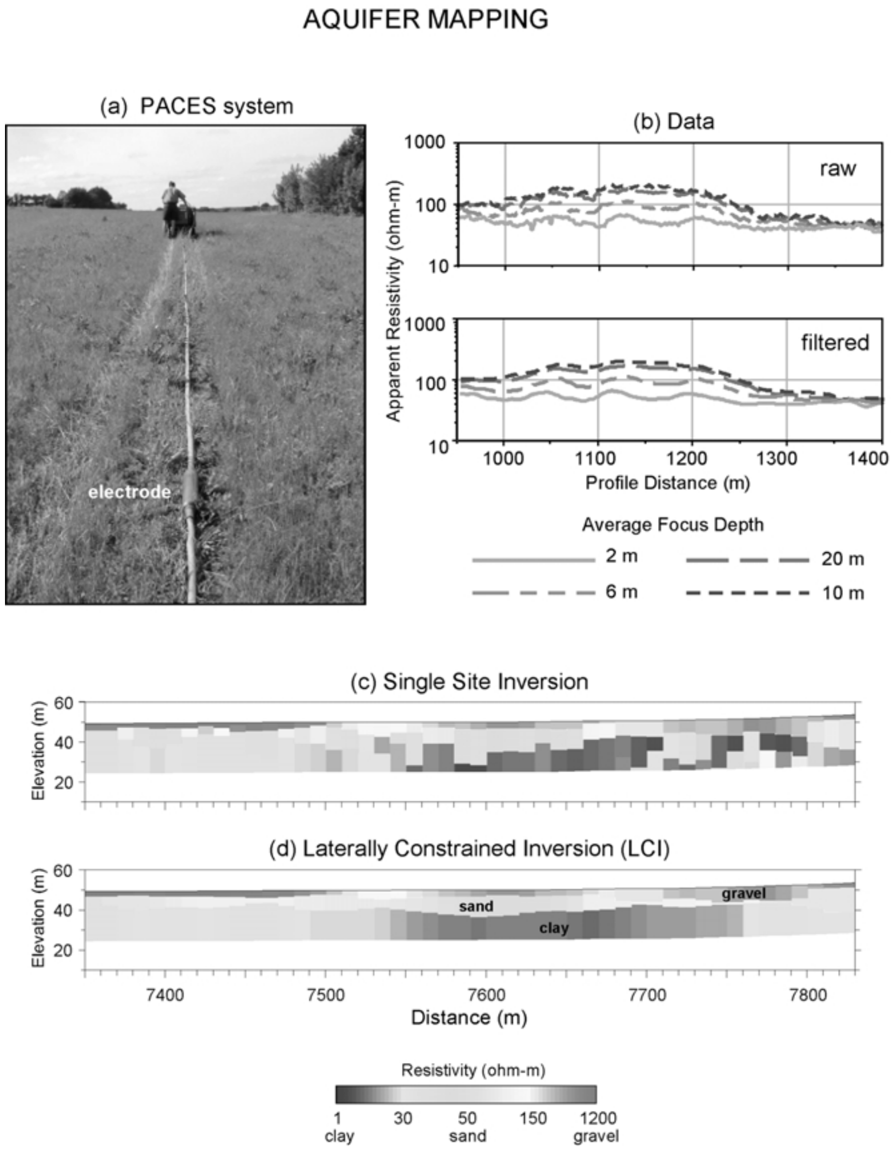

Figure 5. (a) The Århus Pulled Array Continuous Electrical Sounding (PACES) system, (b) raw and filtered profile data, (c) stitched together single site 1D inversion results, and (d) a laterally constrained inversion (LCI) 1D section with clay, sand and gravel noted (Auken et al., 2000).

The PATEM system uses an offset configuration of 25 m, a 3 m by 5 m transmitter loop with two moments of 7500 and 400 Am^2, and a repetition rate of 25 Hz for measurements from 5 microseconds to 8 milliseconds. The system pulled behind a small tractor at a distance of 10 m, as seen in Figure 6a, can be collapsed for navigation through varied terrain. Figure 6a also shows the system in data acquisition mode. In stationary mode the system acquires data equivalent to a commercial TEM system in an offset configuration. Figures 6b and 6c show the measured response, and a 1D inverted section estimating the geometry of the aquifer at depth, respectively.

To further understand groundwater investigations theoretical studies were undertaken on different methodologies (Christiansen and Christensen, 2001; Christensen et al., 2000a, b). The resolution of various airborne and ground based methods is compared within the context of different 1D inversion approaches. The model at the top of Figure 7 is a 2D simulation of a moraine feature of sand and clay lenses over a conductive basement, as is common in Denmark. The subsequent sections are 1D inversion results corresponding to noise-free, synthetic data from the Geonics PROTEM 47 and PATEM ground systems and the World Geoscience TEMPEST and the Geoterrex GEOTEM airborne systems. The figures on the left are stitched together resistivity model sections from a minimum layer 1D inversion and those on the right are from a minimum structure 1D inversion (Poulsen and Christensen, 1999). As expected the ground systems have much higher resolution than the airborne systems and the former show inhomogeneities in the near-surface layer. It is interesting to note how differently the depth to the conductor is mapped for the two airborne systems with the minimum layer inversion when there is a shallow, conductive patch. The major difference between the two airborne simulations is the transmitter waveform.

5.2. Infiltration experiments

The vadose zone is important because it influences recharge to the underlying aquifer and the transfer of contaminants. Typical hydrological instruments, such as tenisometers and neutron probes, used for vadose zone characterization only give point measurements, so obviously this is an area where geophysics can be an effective tool. Several groups are working to understand the behavior of the vadose zone through both laboratory and field experiments (Clement et al., 1999; Hahesy et al., 2000; Robinson et al., 2000). Electrical resistivity is proving to be an effective means of monitoring infiltration of the vadose zone. At a test site at the University of Birmingham, England, daily monitoring of a poorly cemented Triassic sandstone, overlain by roughly 1 m of loam, with a high resolution surface array (254 surface electrodes on a 0.5 m grid) by Hatzichristodulu et al. (1999) showed a complicated geology and resistivity contrasts between 5 and 700 ohm-m. The percentage differences in model resistivity correlated nicely with rainfall data.

Subsurface ERT and cross-hole GPR were used by Yang et al. (2000) and Paprocki and Alumbaugh (1999) to estimate moisture content at the vadose zone facility at the Socorro School of Technology, New Mexico, USA. Figure 8 shows the ERT array with vertical electrode strings of 17 electrodes from the surface to about 14 m depth. The array also included 36 surface electrodes. The white spots depict the location of plastic cased boreholes for neutron logging and the cross-

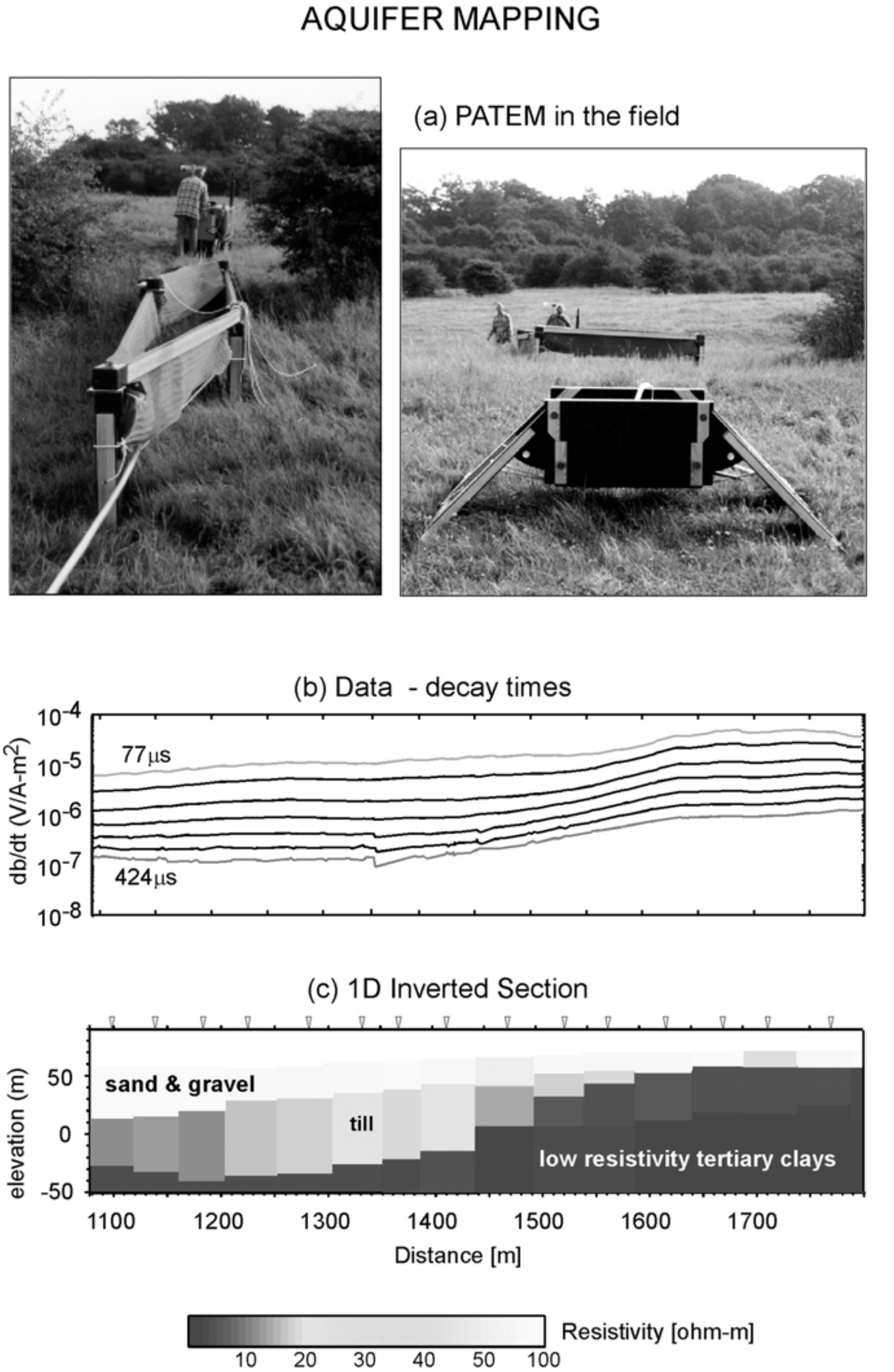

Figure 6. (a) The Århus Pulled Array TEM (PATEM) system in the field, (b) selected decay time of the measured response, and (c) a 1D inverted section estimating the geometry of an aquifer at depth (Sørensen et al., 2000).

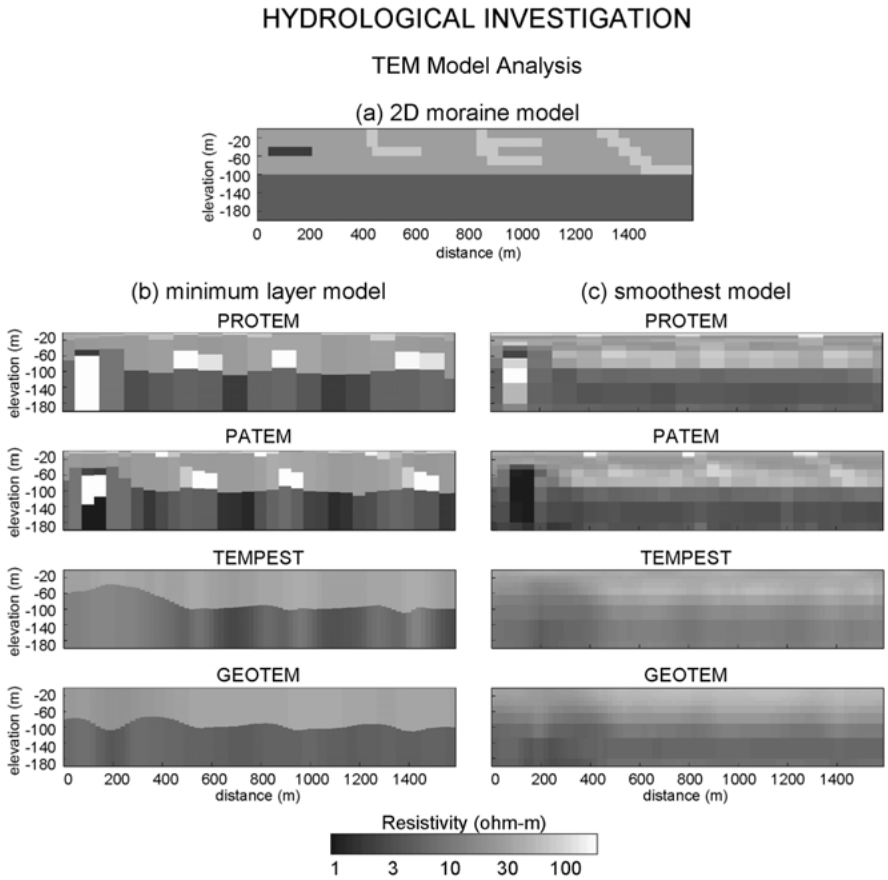

Figure 7. (a) Numerical 2D simulation of a moraine feature, common in Denmark. The subsequent sections are 1D inversion results corresponding to noise-free synthetic data for the Geonics PROTEM 47 and PATEM ground systems, and the World Geoscience TEMPEST and the Geoterrex GEOTEM airborne systems. Figures (b) are of a minimum layer and (c) are of a minimum structure inversion (Christensen et al., 2000b).

hole GPR measurements. An infiltrometer was used to inject 2.5 cc of water/day on the surface in the area depicted by the white box.

A pre-infiltration image (not shown) was developed first. Data were then recorded to show changes with time. The series in Figure 8 show the change in moisture content estimated from the ERT data as a function of time. The dark areas show the increase in moisture content. Information from neutron log data is restricted to the area close to the borehole. However moisture content estimates were enhanced by cokriging the ERT and neutron log data. The GPR results were comparable with that from the ERT to estimate the subsurface moisture content, but the method was more labor intensive and results were limited to 2D planes.

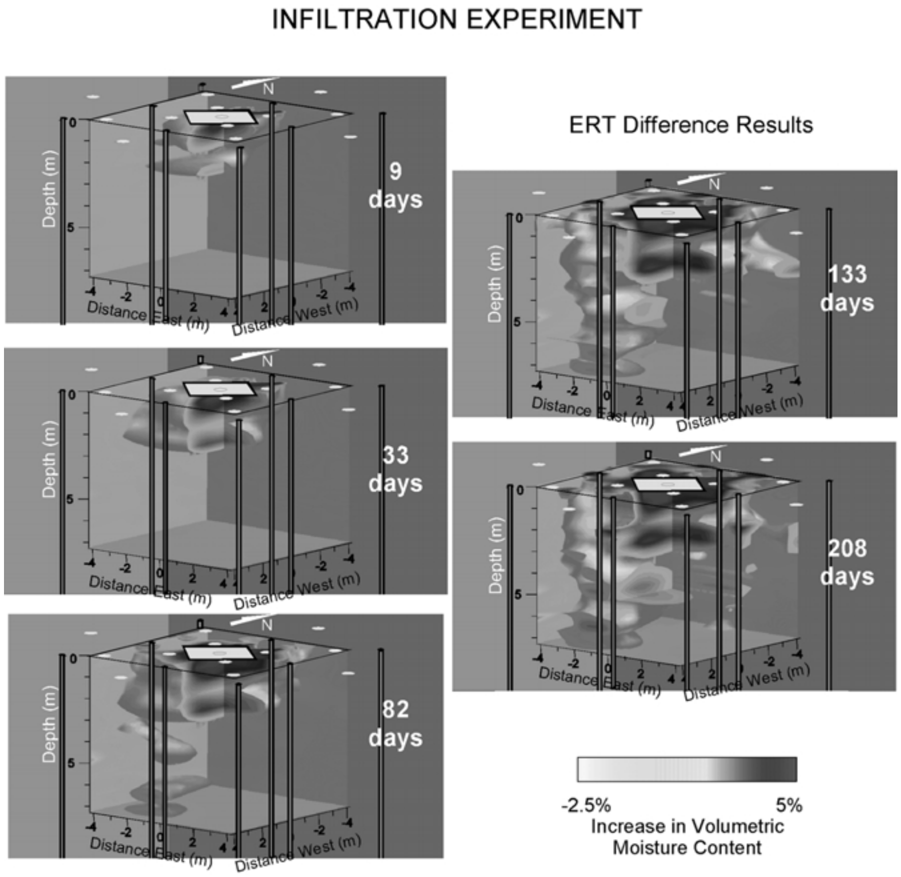

Figure 8. Subsurface Electrical Resistance Tomography (ERT) array used to estimate moisture content at the vadose zone facility at the Socorro School of Technology, New Mexico. The vertical electrode strings contained 17 electrodes from the surface to about 14 m depth. The white spots depict the location of plastic cased boreholes for neutron logging and cross-hole GPR measurements. Figures show the change in moisture content as a function of time; the dark areas show the increase in moisture content (Yang et al., 2000).

6. Site Characterization

6.1. Buried waste and landfill

The traditional tools for buried waste and landfill characterization have been a combination of GPR, magnetics and conductivity mapping. GPR works well when the cover is resistive, but most often clay is used as a protective cap and the GPR signal is strongly attenuated. Magnetometers and conductivity meters are rapid survey instruments that can be used to detect many metallic and conductive objects, but they are profiling techniques that give limited depth information. Measuring the in-phase in addition to the quadrature component increases the accuracy of a conductivity survey. EM sounding methods give needed depth information. Lohva et al. (1999), Pellerin and Labson (2000), and Siemon et al. (2000) have shown that helicopter EM methods can successfully delineate hazardous waste sites. A favorite technique in the EM community, magnetotellurics (MT), has been shown to be extremely useful for buried waste characterization when used at radio (RMT) frequencies (Greinwald et al., 1999; Recher et al., 2000). Even though it was 25 years ago when Angoran et al. (1974) showed IP to be a highly successful method for landfill characterization, it has only been in recent years that resistivity and IP are becoming efficient for waste site characterization (Carlson et al., 1999; Ilicaet and Morelli, 1999; Lewis et al., 2000; Panissod et al., 2000; and Recher et al., 2000).

Although the results are very impressive, the IP method was probably slow to receive acknowledgment in buried waste applications because it is a slow, laborious technique. The system developed by Zonge Engineering (Carlson et al., 1999) is rapid enough to make IP a competitive methodology in environmental investigations. Figure 9 shows 20 ft (6.1 m) depth slice of 2D inversion results of (a) resistivity and (b) chargeability over a landfill in Tucson, Arizona, USA. These results are impressive in several ways. First, the data were collected using a fast multiplexer system that enabled a 3-person crew to cover 1–2 acres/day with a 7.5 ft (2.3 m) station spacing and 20–30 ft (6–9 m) line spacing. Magnetic and conductivity data were also collected, but only the IP response accurately delineated the waste. Inspection of the figures shows two areas outlined by a dashed line. The elongated area in the center of the maps defines a berm in the landfill.

The resistivity low that overlaps the berm coincides with an old pit in the aerial photos that has been excavated and backfilled with sand, so the resistivity detected a pit, but not the waste. The second outlined area corresponds to the waste defined by the IP response and later confirmed with drilling. The small IP anomaly in the top center of the map was due to sand, which had an IP response when subsequently measured in the laboratory. It is interesting to note that a magnetic and conductivity survey was also performed at this site. The apparent conductivity data matched the resistivity results, and the magnetics showed some surface construction debris, but neither system delineated the waste delineated with IP. The strong IP response was probably due to oxidized iron (rust) in the landfill.

6.2. Geological mapping

Geological mapping has always been an important task for geophysics with a variety of applications. In the context of environmental and geotechnical problems, it is often used for pre-investigation of engineering projects such as landfills, bridges, tunnels and dams or the mapping of landslides (Gabbani et al., 2000; Lapenna et al., 2000; Sretenovic et al., 2000; Yaramanci and Kiewer, 2000) and subsidence areas (Fenning et al., 2000). Resistivity is the predominant method used for large scale pre-investigation studies. The ABEM Lund system (Dahlin, 1996) was used

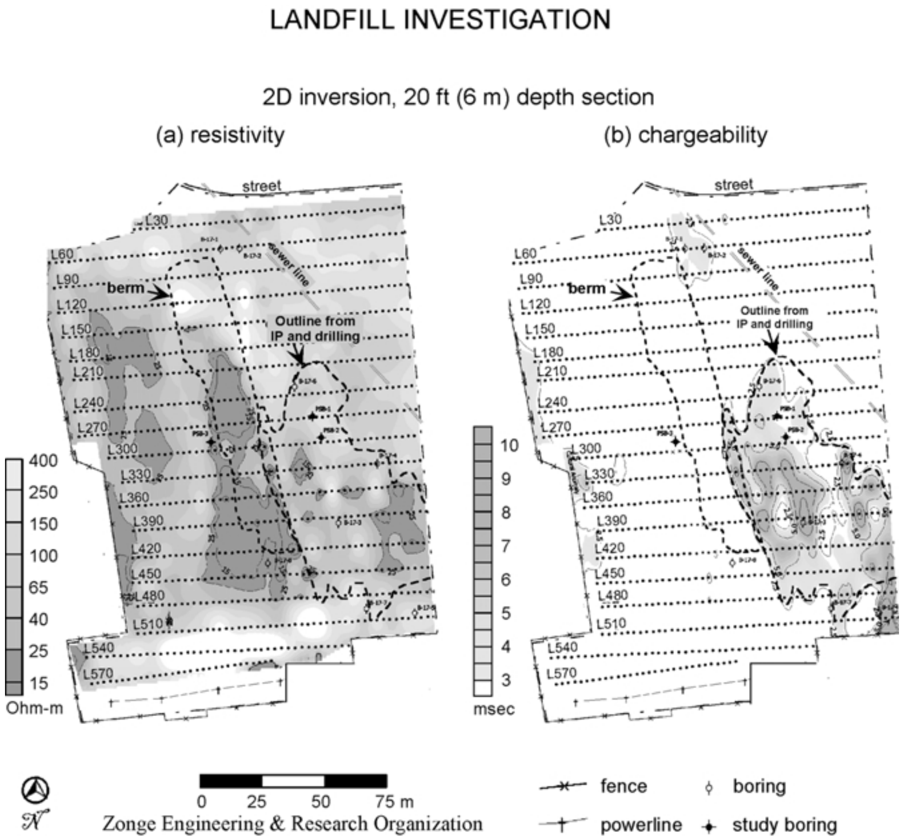

Figure 9. Depth slices at 20 ft (6.1 m) of a 2D (a) resistivity and (b) chargeability inverse model from a landfill in Tucson, Arizona, USA. As noted, dashed lines outline the waste delineated by IP and drilling and a surface berm. Data were acquired with the Zonge 'extremely fast' IP system (after Carlson et al., 1999).

for the Hallandsaas, Sweden tunnel site (Dahlin et al., 1999; Marache et al., 2000) and other urban pre-investigations (Wisén et al., 2000). Lagabrielle et al. (2000) mapped alluvium with a resistivity survey under sea water for the new harbor at Le Havre, France. Hodges et al. (2000) used helicopter EM as an aid to planning and monitoring pipeline construction in southern Quebec, Canada. Satti et al. (2000) performed an integrated geophysical study, which included magnetics, frequency EM, TEM and GPR, to map near-surface faults in the Wilcox Group, Texas, USA in support of the expansion of a lignite mine. Resistivity and EM was used by El-Hussain et al. (2000) to delineate and characterize buried paleochannels of the Mississippi River in the New Madrid seismic zone of southeastern Missouri, USA.

Along with a variety of interesting applications, instrumentation has been adapted and developed for geological mapping purposes in environmental applications. Airborne techniques continue to be used for environmental mapping (Macnae and

Yang, 1999; Beamish et al., 2000), but the newest developments are with ground systems. The RMT method has been shown to be an effective method in environmental applications (Zacher et al., 1996). Pedersen et al. (1999) developed a new tensor system, EnviroMT, that uses either ambient signal or a controlled source above 14 kHz, synchronous detection and has a built-in database handling system.

Capacitively coupled resistivity systems allow for continuous resistivity measurements at relatively high speed (Pellerin and Alumbaugh, 1997). While there is work underway on the theoretical and practical aspects (Kuras, 2000), the significant break through accomplishments have been in instrumentation. Two systems recently came on the market: the Iris CORIM system and the Geometrics OhmMapper. The systems operate at 12 and 16 kHz, respectively, with electrodes having very different geometries. Figure 10 shows the results of an OhmMapper survey performed in Western Wisconsin, USA (J. Johnston, Geometrics, and J.C. Hanson, WREDCO GeoSurveys, personal communication). Best suited for resistive terrain, the purpose of this survey was to map depth to the shallow quartzite bedrock and high angle faulting and fracturing. Discontinuous argillite beds lying within the quartzite were also a mapping target. Data were collected using 5 m dipoles, in the dipole-dipole configuration, and a N-spacing of 1, 2, 3, 5 and 7 for investigation of the top 11 m. The measured and calculated apparent resistivity are shown in Figures 10a and 10b, respectively. The interpreted faults and fractures, and location of a well are annotated on the 2D inverted section (Loke, 1998). The results correlate quite well with the drill hole and well log.

7. Very Difficult Problems

In contrast to landfill and buried waste characterization some problems, such as voids and small objects, do not lend themselves to inductive techniques. However the problems are important and optimistic researchers persevere.

7.1. Caves, Karsts and Cavities

This category of problems can generally be referred to as the search for a void (resistor) in a conductor – nearly impossible with inductive techniques and only slightly better with galvanic methods. Seismic and GPR methods are more favorable, but EM and electrical techniques can be part of an integrated program. If a tunnel contains wires or cabling, or a karst or sinkhole is filled with clay, the problem becomes a search for a conductor – much easier for EM.

Researchers at the Massachusetts Institute of Technology (MIT), Earth Resources Laboratory have been making a concerted effort to develop effective cave mapping systems. Sogade et al. (1999) developed a loop-loop EM system calibrated with laboratory analysis with some success. Morgan et al. (1999) used a comprehensive, resistivity data gatherer scheme with 2D inversion with surprisingly good results. Sogade et al. (1999) used IP over the same cave system with

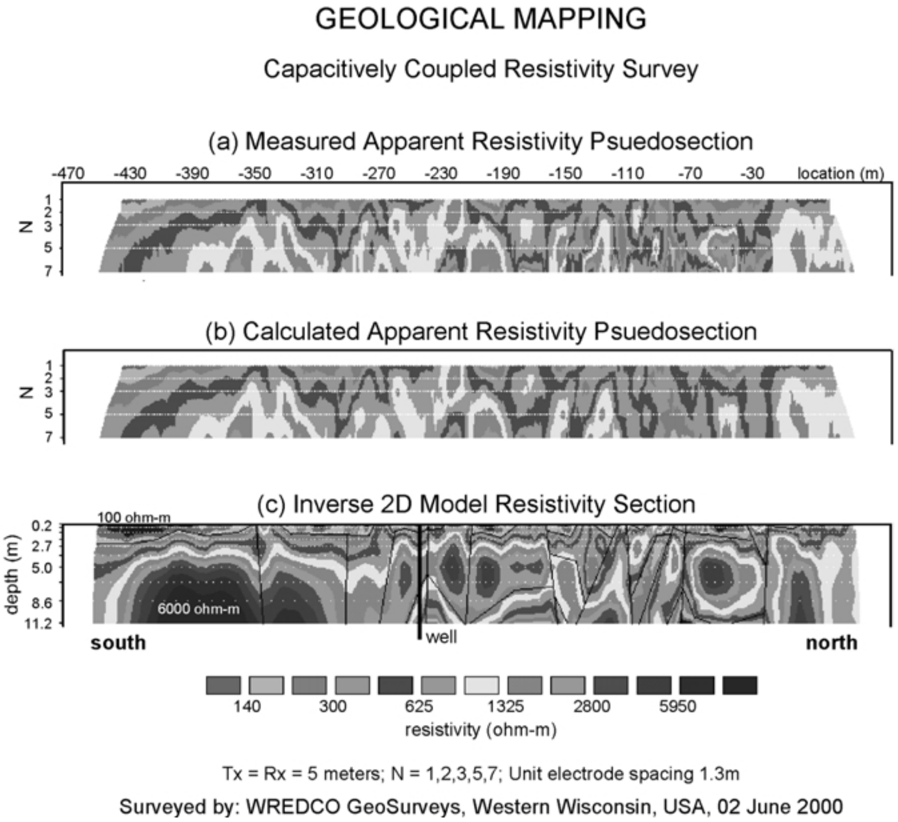

Figure 10. (a) The measured and (b) calculated apparent resistivity, and (c) the 2D inverted section for OhmMapper data acquired in Western Wisconsin, USA. The interpreted faults and fractures, and location of a well are annotated on (c). Resistivity values in the near surface are in 100 s of ohm-m and in thousands at depth (Hanson and Johnston, personal communication).

comparable results. Taking an indirect approach Vichabian and Morgan (1999) used SP to determine ground water flow during two different seasons and concluded that the approach is accurate only under certain conditions – the cave is a sink for water flow and the near-surface is dry. In addition to the MIT group, Fancsik and Nyari (1999) are processing geoelectric data with a deconvolution filtering method for cavity detection, and Ezersky et al. (2000) are investigating the Soreq Cave area in Israel with geoelectrics.

Sinkhole collapse is a serious limitation in the development of karst areas, especially when the bedrock is covered with unconsolidated material. Intrusive methods (drilling) have a low probability of encountering karst features and rely on a hit-or-miss approach; geophysical surveying can increase identification of areas of potential collapse. Zhou et al. (1999) used ERT to define the bedrock/overburden boundary in the covered karst terrain of southern Indiana, USA with reasonable results. However, the authors warned that the tomograms should be interpreted cautiously, even with the aid of ground truth. Roth et al. (1999) used the Lund ABEM multi-electrode resistivity system on the fractured, carbonate bedrock in the northeastern USA. Processing the data with the 2D inversion algorithm of Loke (1998), the method proved to be effective at locating subsurface features, but it was stated that work remains to refine the method and interpretation. Seismic, GPR and resistivity surveys were performed by El-Behiry (2000) south of Cairo, Egypt to locate sinkholes, active karsts, and solution enlarged fractures. GPR outlined a depression feature and seismic refraction expressed the medium as highly fracture limestone, but resistivity delineated the sinkhole.

7.2. Unexploded ordnance (UXO)

The problem of detecting and identifying UXO and land mines is very difficult and very important. It is difficult for a number of reasons. Land mines are often made of plastic, containing as little as 1–3 grams of metal. The identification of UXO is a complex problem because of the incredible number of ordnance with different geometries and the orientations in which they can be found – all of which have a different electromagnetic coupling and resulting response. Land mines and UXO are found in geological environments as varied as the sands of Kuwait, the mountains of Bosnia or the rice fields of Thailand and Cambodia. The technical problems are coupled with the demands of the military that there be a 100% accurate hit rate – no false negatives or false positive. Although some may feel this is a hopeless geophysical problem, the problem is literally a matter of life and death and must be addressed.

Recent research can be divided into three main categories: identification of given ordnance by an analysis of the broadband EM spectral response, testing to evaluate methodologies, and development of platforms to expand spatial coverage. Saunders et al. (2000) has developed a new location system utilizing ultrasonic technology for positioning of a Geonics EM-61 metal detector in wooded terrain. Bowers and Grounds (2000) have developed a kinematic survey system that utilizes centimeter accuracy GPS and GIS technology on a ground platform for induction and magnetic sensors. On an aerial platform Doll et al. (1999) have evaluated EM, magnetic, multi-spectral and thermal data finding that one would have to fly as low as 5 m for the EM sensor to be effective. Daily et al. (2000) had limited success with an IP experiment using their electrical impedance tomography system; the IP response is present only when there is a soil-metal polarization.

Spectral analysis seems to be the area receiving the most attention. The time-domain decay has a characteristic response for a given target geometry and orientation. Pasion and Oldenburg (1999) and Snyder et al. (2000) have performed theoretical modeling to quantify these responses, and the latter group has also included an empirical study. Working in the frequency domain Barrow et al. (2000), Keiswetter et al. (1999, 2000), Miller et al. (2000) and Won et al. (2000) have developed a hand held monostatic sensor (GEM-3) and corresponding modeling

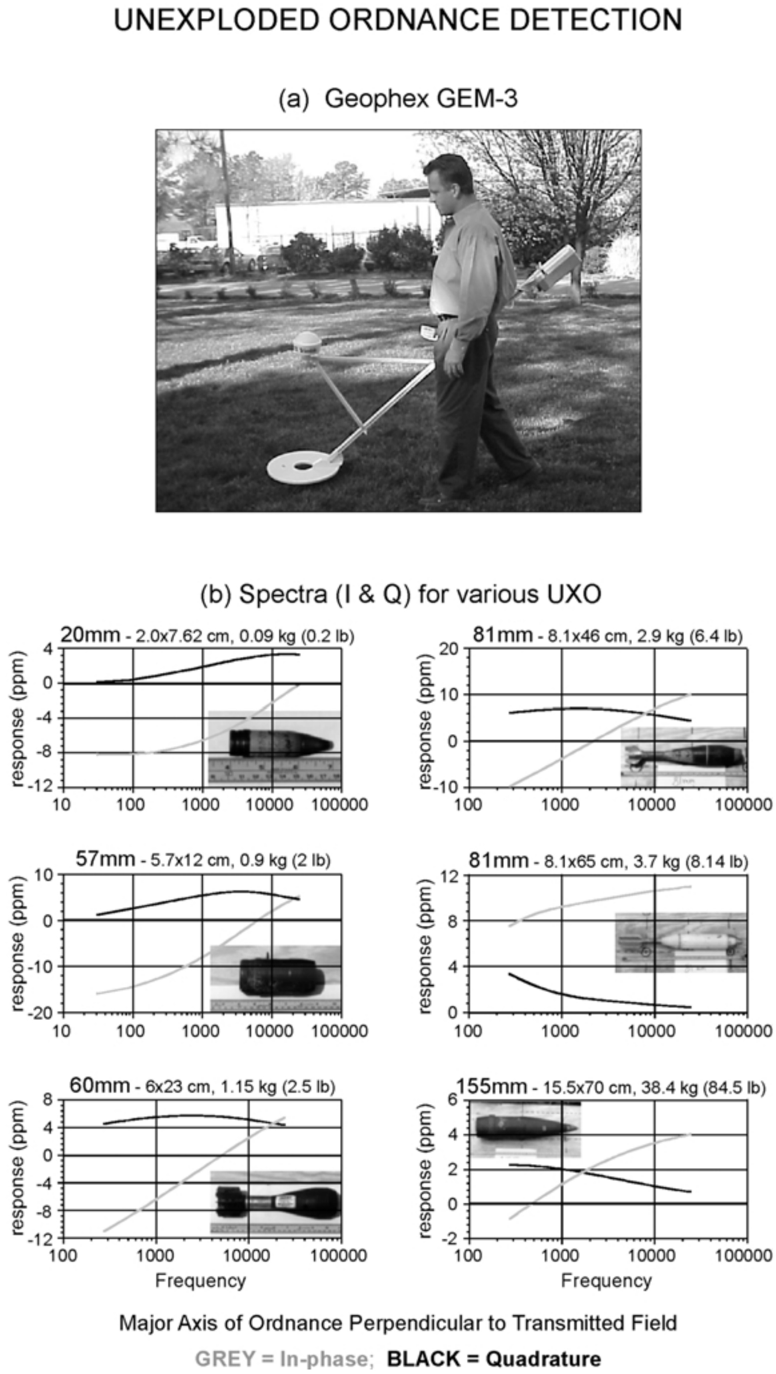

Figure 11. (a) The Geophex GEM-3 instrument, and (b) the in-phase and quadrature responses for selected ordnance. Responses, reported as ppm of the primary field, were made with the major axis of the ordnance perpendicular to the GEM-3 (after Keiswetter et al., 1999).

algorithms to characterize ordnance and land mines. Figure 11a shows the GEM-3 instrument and Figure 11b shows the in-phase and quadrature responses for selected ordnance, which range from 20 to 155 mm in size. Responses were made with the major axis of the ordnance perpendicular to the GEM-3. The distinctiveness of the responses is encouraging. However because of the multitude of type and orientation of ordnance it is only possible to get a one-to-one mapping of these responses to the ordnances when a limited number are present in the survey area.

8. Summary

As is clear from the extensive list of references, there is a broad breath of applications for electrical and electromagnetic methods in environmental and geotechnical geophysics. The important contributions to instrumentation focus on continuous, or very dense, rapid measurement systems. The PACES and PATEM systems with corresponding robust interpretational software have been developed for hydrogeological investigations. A mobile galvanic, pole-pole resistivity system has been developed for archaeological and pedological surveys and a capacitively coupled pull-along resistivity system is now available for shallow mapping in resistive terrain. Rapid IP systems are also being used for contaminant and landfill mapping with great success. And at the inductive limit, the VETEM system is operating in areas where GPR is not effective. Although 1D inversion software has matched the advances in instrumentation, multi-dimensional interpretational schemes must be developed to continue these advances. As instrumentation and interpretational software continue to become more accurate and efficient, geophysical surveying will increase its value as a tool in environmental investigations.

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