Recent developments in the direct-current geoelectrical imaging method

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A B S T R A C T

There have been major improvements in instrumentation, field survey design and data inversion techniques for the geoelectrical method over the past 25 years. Multi-electrode and multi-channel systems have made it possible to conduct large 2-D, 3-D and even 4-D surveys efficiently to resolve complex geological structures that were not possible with traditional 1-D surveys. Continued developments in computer technology, as well as fast data inversion techniques and software, have made it possible to carry out the interpretation on commonly available microcomputers. Multi-dimensional geoelectrical surveys are now widely used in environmental, engineering, hydrological and mining applications. 3-D surveys play an increasingly important role in very complex areas where 2-D models suffer from artifacts due to off-line structures. Large areas on land and water can be surveyed rapidly with computerized dynamic towed resistivity acquisition systems. The use of existing metallic wells as long electrodes has improved the detection of targets in areas where they are masked by subsurface infrastructure. A number of PC controlled monitoring systems are also available to measure and detect temporal changes in the subsurface. There have been significant advancements in techniques to automatically generate optimized electrodes array configurations that have better resolution and depth of investigation than traditional arrays. Other areas of active development include the translation of electrical values into geological parameters such as clay and moisture content, new types of sensors, estimation of fluid or ground movement from time-lapse images and joint inversion techniques. In this paper, we investigate the recent developments in geoelectrical imaging and provide a brief look into the future of where the science may be heading.

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1. Introduction

The resistivity survey method is one of the oldest and most commonly used geophysical exploration methods (Reynolds, 2011). It is widely used in environmental and engineering (Chambers et al., 2006; Dahlin, 2001; Rucker et al., 2010), hydrological (Page, 1968; Wilson et al., 2006), archeological (Griffiths and Barker, 1994; Tsokas et al., 2008) and mineral exploration (Bauman, 2005; Legault et al., 2008; White et al., 2001) surveys. It has been used to image structures from the millimeter scale to kilometers (Linderholm et al., 2008; Storz et al., 2000). Besides surveys on the land surface, it has been used across boreholes (Chambers et al., 2003; Daily and Owen, 1991) and in aquatic areas (Loke and Lane, 2004; Rucker et al., 2011b).

Since the first commercial use of the resistivity method in the early 1920’s (Burger et al., 2006) and right up to the late 1980’s, it has been used essentially as a one-dimensional (1-D) mapping method. However, even in moderately complex areas, a 1-D approach is not sufficiently accurate. Over the last 25 years, there have been revolutionary improvements to the resistivity method where two-dimensional (2-D) surveys are now routinely conducted. Three-dimensional (3-D) surveys are widely used in areas with complex geology, while there have been significant interest and developments in four-dimensional (4-D) surveys. This has been made possible by recent developments in field instrumentation, automatic interpretation algorithms, and computer software. With the new tools, complex variations of the subsurface resistivity in both space and time can now be accurately mapped.

In this review, we summarize key developments in the field of geoelectrical characterization and monitoring from the past two decades. The review is focused more towards the commercial development of the method, and is complementary to the research oriented reviews presented by Slater (2007) and Revil et al. (2012). It is largely focused on the D.C. resistivity method due to space constraints, with references to related methods such as induced polarization (I.P.) and spectral I.P. methods where appropriate.

The following section gives a short description of basic principles of the resistivity method and traditional 1-D resistivity mapping.
methods. This is followed by brief overviews of recent developments in 2-D, 3-D and 4-D surveying methods, and practical applications in various fields. Finally new developments in a few specific areas that point to future trends are described.

2. Basic principles of the resistivity method

The relationship between the electrical resistivity, current and the electrical potential is governed by Ohm’s Law. To calculate the potential in a continuous medium, the form of Ohm’s Law, combined with conservation of current, as given by Poisson’s equation is normally used. The potential due to a point current source located at \( x_s \) is given by

\[
\nabla \cdot \left[ \frac{1}{\rho(x,y,z)} \nabla \phi(x,y,z) \right] = -\frac{\partial j_c}{\partial t}(x_s)
\]

where \( \rho \) is the resistivity, \( \phi \) is the potential and \( j_c \) is the charge density. The potential at any point on the surface or within the medium can be calculated if the resistivity distribution is known. This is the forward problem, and we specifically separate it from the inverse problem discussed below. For 1-D models (Fig. 1), the forward problem is commonly solved using the linear filter method (Ghosh, 1971). For 2-D and 3-D models, analytical methods are used for simple structures such as a cylinder or sphere in a homogeneous medium (Ward, 1982; Ward and Hohmann, 1987). Boundary and analytical element methods (Furman et al., 2002; Spiegel et al., 1980; Xu, 2001) can also be used for more general structures but are usually limited to models where the subsurface is divided into a relatively small number of regions. For modeling of field data, the finite-difference and associated finite volume methods (Dey and Morrison, 1979a,b; Pidliesky et al., 2007), and the finite-element (Coggon, 1971; Holcombe and Jiracek, 1984) method are more commonly used. These methods discretize the subsurface into a large number of cells. By using a sufficiently fine mesh and the proper boundary conditions, an accurate solution for the potential over complex distributions of resistivity can be obtained. In areas where anisotropy is significant (LaBreque and Casale, 2002), Eq. (1) is modified where the resistivity is a vector that includes directional dependent values instead of a scalar function.

The purpose of the resistivity method is to calculate the electrical resistivity of the subsurface, which is an unknown quantity. The measurements for the resistivity survey are made by passing a current into the ground through two current electrodes (usually metal stakes), and measuring the difference in the resulting voltage at two potential electrodes. In its most basic form, the resistivity meter has electrodes, the current \((I)\) injected into the ground and the resulting voltage difference \((\Delta V)\) between the potential electrodes (Fig. 2). The current and voltage measurements are then converted into an apparent resistivity \((\rho_a)\) value by using the following formula

\[
\rho_a = k \frac{\Delta V}{I},
\]

where \( k \) is the geometric factor that depends on the configuration of the current and potential electrodes (Koefoed, 1979). Eq. (2) represents the simplest form of the inverse problem and assumes that the earth is homogeneous for each combination of current and potential measurements. Different arrangements of the current and potential electrodes (or arrays) have been devised over the years. The most commonly used arrays are shown in Fig. 2, along with their associated geometric factors. The advantages and disadvantages of the different arrays are discussed in various papers; such as in Dahlin and Zhou (2004), Saydam and Duckworth (1978), Szalai and Szarka (2008) and Zhou et al. (2002). The suitability of an array depends on many factors; among which are its sensitivity to the target of interest, signal-to-noise ratio, depth of investigation, lateral data coverage and more recently the efficiency of using it in a multi-channel system. The multiple gradient array (Fig. 2F) was designed for use in multi-channel systems (Dahlin and Zhou, 2006).

3. Resistivity acquisition, processing and interpretation

3.1. Traditional 1-D resistivity surveys

From the 1920’s to the late 1980’s there were essentially two surveying techniques used, the profiling and sounding methods. In a profiling survey, the distances between the electrodes were kept fixed and the four electrodes were moved along the survey line. A related technique is the mise-a-la-masse method where one electrode is embedded into a conductive body (with the second current electrode at a sufficiently far distance) and the potential electrodes are moved around it to produce an equipotentials map (Parasnis, 1967). The data interpretation for profiling and mise-a-la-masse surveys were mainly qualitative. In the sounding method (Koefoed, 1979) the center point of the electrodes array remained fixed but the spacing between the electrodes was increased to obtain information about the deeper sections of the subsurface. Usually the Wenner or Schlumberger arrangement was used.

The interpretation model consisted of a series of 1-D horizontal layers (Fig. 1A), and the sounding method has been extensively used to investigate the ground for resource management, such as

Fig. 1. Resistivity sounding (A) and best-fit three-layer model interpretation (B) for a sand and gravel reconnaissance survey in the Thames Valley, UK. Note: upper layer, silt (32 \(\Omega.m\)); middle layer, river terrace sand and gravel (205 \(\Omega.m\)); lower layer, Oxford Clay (11 \(\Omega.m\)).
mineral, petroleum, and groundwater resources. Initially quantitative interpretation of geoelectric sounding data was conducted by using pre-computed or ‘standard’ sounding curves. Sounding curves were later superseded by computer inversion techniques with the advent of the linear filter method (Ghosh, 1971; Koefoed, 1979).

The modern application of resistivity processing includes inverse modeling. A commonly used method for sounding data inversion is the damped least-squares method (Inman, 1975), based on the following equation:

\[
J^T J + \lambda I \Delta q = J^T \Delta g.
\]

where, the discrepancy vector \( \Delta g \) contains the difference between the logarithms of the measured and the calculated apparent resistivity values and \( \Delta q \) is a vector consisting of the deviation of the estimated model parameters from the true model. Here, the model parameters are the logarithms of the resistivity and thickness of the model layers. \( J \) is the Jacobian matrix of partial derivatives of apparent resistivity with respect to the model parameters. \( \lambda \) is a damping or regularization factor that stabilizes the ill-condition Jacobian matrix usually encountered for geophysical problems. Starting from an initial model (such as a homogeneous earth model), this method iteratively refines the model so as to reduce the data misfit to a desired level (usually less than 5%). Other methods such as the conjugate gradient method, SVD analysis and global optimization methods (including neural networks and simulated annealing) have also been used for resistivity data inversion (Pellerin and Wannamaker, 2005). Fig. 1 shows an example of the results from a resistivity sounding survey using the offset Wenner array (Barker, 1981) that has a three-layer inversion model.

The main weakness of the sounding method is the assumption that there are no lateral changes in the resistivity. It is useful in geological situations where this is approximately true, but gives inaccurate results where there are significant lateral changes. The effect of lateral variations on the sounding data can be reduced by using the offset Wenner method (Barker, 1981) but for more accurate results the lateral changes must be directly incorporated into the interpretation model. It should be noted that some early combined sounding and profiling surveys to produce 2-D pseudosections were carried out for mineral exploration (Ward, 1990), usually together with I.P. measurements. Conducting the surveys and quantitative modeling using manual adjustments of a forward model (Hohmann, 1982) was laborious and thus such surveys were comparatively rare.

3.2. Multi-electrode systems and 2-D imaging surveys

While the resistivity meter used in sounding and profiling surveys typically has four electrodes connected via four separate cables, a multi-electrode system has 25 or more electrodes connected to the resistivity meter via a multi-core cable (Griffiths et al., 1990) and since then have become a standard tool in many geological organizations. An internal switching circuitry controlled by a programmable microcomputer or microprocessor within the resistivity meter automatically selects the appropriate 4 electrodes for each measurement. This enables almost any array configuration to be used. By making measurements with different spacings at different locations along the cable, a 2-D profile of the subsurface is obtained. Together with the parallel development of fast and stable automatic data inversion techniques (deGroot-Hedlin and Constable, 1990;
Li and Oldenburg, 1992; Loke and Barker, 1996a) that could be implemented on commonly available microcomputers. 2-D electrical imaging surveys became widely used in the early 1990’s.

A 2-D model that consists of a large number of rectangular cells is commonly used to interpret the data (Loke and Barker, 1996a). The resistivity of the cells is allowed to vary in the vertical and one horizontal direction, but the size and position of the cells are fixed. Again, different numerical methods can be used to calculate the potential values for the 2-D forward model. Inverse methods are then used to back calculate the resistivity that gave rise to the measured potential measurements. Starting from a simple initial model (usually a homogeneous half-space), an optimization method is used to iteratively change the resistivity of the model cells to minimize the difference between the measured and calculated apparent resistivity values. The inversion problem is frequently ill-posed and ill-constrained due to incomplete, inconsistent and noisy data. Smoothness or other constraints are usually incorporated to stabilize the inversion procedure to avoid numerical artifacts. As an example, the following equation includes a model smoothness constraint to the least-squares optimization method,

\[
(\mathbf{J}^T \mathbf{J} + \lambda \mathbf{F}) \Delta \mathbf{q}_k = \mathbf{J}^T \mathbf{g}_k - \lambda \mathbf{F} \mathbf{q}_{k-1},
\]

where

\[
\mathbf{F} = \alpha_x \mathbf{C}_x^T \mathbf{C}_x + \alpha_z \mathbf{C}_z^T \mathbf{C}_z.
\]

\(\mathbf{C}_x\) and \(\mathbf{C}_z\) are the roughness filter matrices in the horizontal (x) and vertical (z) directions and \(\alpha_x\) and \(\alpha_z\) are the respective relative weights of the roughness filters. \(k\) represents the iteration number. One common form of the roughness filter is the first-order difference matrix (deGroot-Hedlin and Constable, 1990), but the elements of the matrices can be modified to introduce other desired characteristics into the inversion model (Farquharson, 2008; Pellerin and Wannamaker, 2005). An L1-norm criterion can be used to produce ‘blocky’ models for regions that are piecewise constant and separated by sharp boundaries (Farquharson and Oldenburg, 1998; Loke et al., 2003). The laterally constrained inversion method (Auken and Christiansen, 2004) that includes sharp boundaries has been successfully used in areas with a layered subsurface structure. Joint inversion algorithms using other geophysical or geological data to constrain the model have also been implemented to help produce models that are consistent with known information (Bouchetta et al., 2012; Hinnell et al., 2010; Linde et al., 2006a). A number of micro-computer based software are now available that can automatically carry out the inversion of a 2-D survey data set in a very short period of time.

There are many commercial multi-electrode resistivity systems capable of connecting up to several hundreds of electrodes at once, with electrode spacings practically varying from 1 to 20 m. A recent development over the past 10 years is multi-channeled systems that can greatly reduce the survey time. Only two electrodes can be used as the current electrodes at a single time, but the voltage measurements can be made between many different pairs of potential electrodes. Commercial systems with 4 to 10 channels are widely available, and some customized systems have more than 100 channels (Rucker et al., in press; Stummer et al., 2002). New data acquisition techniques, such as using the multiple gradient array (Dahlin and Zhou, 2006), have been designed for the multi-channeled systems.

Fig. 4A shows an apparent resistivity pseudosection from a survey using the dipole–dipole array to map shallow Quaternary deposits at the Eddleston experimental site, Scottish Borders, UK (Dochartaigh et al., 2011). The dipole–dipole array was used with the dipole length ‘a’ ranging from 3 to 18 m, and the dipole separation factor ‘n’ ranging from 1 to 8. The mid-point of the array was used to set the horizontal location of the plotting point in the pseudosection, while the ‘median depth of investigation’ method was used to calculate the vertical position (Edwards, 1977). The southern (left) half of the line lies in a floodplain where it crosses a small stream, while the northern (right) half crosses over into grasslands above the floodplain. The relatively flat southern section is characterized by a low resistivity top layer consisting of present-day alluvial deposits, with a general increase in the resistivity towards the northern end located on slightly elevated grasslands (Fig. 4B). The higher resistivity layer at a depth of 5 to 15 m corresponds to a coarser alluvial layer with some gravels.
Two-dimensional (and three-dimensional) electrical imaging surveys are now widely used for mineral, engineering, environmental and archeological surveys. The main limitation of the 2-D surveying method is the assumption that the geological structures do not change in the direction perpendicular to the survey line. This is a reasonable assumption when the survey line can be laid out perpendicular to the strike of the structure. However, when there are significant offline variations, distortions in the model produced can lead to erroneous interpretation. Nevertheless, 2-D imaging surveys are still probably the most widely used technique applied commercially. It can be rapidly carried out at a relatively low cost with lower equipment requirements compared to 3-D surveys (following section) that in many situations makes it the method of choice due to economic (and in some cases physical) constraints. In some situations, correction factors can be calculated for the 3-D effects (Wiwattanachang and Giao, 2011) to greatly reduce the distortions in the 2-D model.

3.3. 3-D imaging surveys

A 3-D resistivity survey and interpretation model should give the most accurate results as all geological structures are 3-D in nature. Although at present it has not reached the same level of usage as 2-D surveys, it is increasingly more widely used in complex areas for many environmental and engineering problems (Chambers et al., 2006; Dahlin et al., 2002; Jones et al., 2012). It is probably more widely used in mineral exploration surveys (Legault et al., 2008; White et al., 2001) where the higher costs involved in securing equipment and control. Loke and Dahlin (2010) describe techniques to reduce artifacts (Fig. 2G) designed by White et al. (2001) to cover a large area efficiently is particularly popular in 3-D I.P. surveys for mineral exploration.

The data interpretation techniques used for 2-D surveys can be extended to 3-D surveys with relatively few modifications (Loke and Barker, 1996b). Fast computer software that takes minutes to hours to invert a 3-D data set (depending on the size of the data set) on common multi-core PCs is now available (Loke, 2012; Rucker et al., in press).

Fig. 5 shows an example of the results from a 3-D survey. The survey was carried out within the valley of the Great Ouse, near the village of Willington to the east of Bedford, UK to map sand and gravel deposits (Chambers et al., 2012). The survey covers an area of 93 × 93 m using 32 orthogonal survey lines with a spacing 6 m between the lines (Fig. 5A). The dipole–dipole array was used with an inline unit electrode spacing of 3 m. The use of an inter-line spacing of twice the inline spacing is common in 3-D surveys using orthogonal 2-D lines (Charibi and Bentley, 2005). After filtering out data points with high reciprocal errors, the final data set used for the inversion has 10,952 points. The inversion model (Fig. 5B) shows a thin near surface layer of about 60 Ωm that corresponds to clay-rich alluvium overlying sand and gravel deposits with higher resistivity values of about 125 Ωm. The Oxford Clay bedrock has a distinctly lower resistivity of about 15 Ωm. The middle sand and gravel layer are incised at places by silt and clay-rich alluvial river deposits. The distribution and thickness of the sand and gravel deposits estimated from the resistivity model were generally in good agreement with logs from a number of boreholes.

3.4. 4-D imaging surveys

In 4-D surveys, the change of resistivity in both space and time is measured. Measurements are repeated at different times using the same 2-D survey line or 3-D survey grid. These surveys include the monitoring of dams sites (Sjödahl et al., 2008), areas prone to landslides (Supper et al., 2008), methane gas generation in landfills (Rosqvist et al., 2011), movement of water in aquifers (Cassiani et al., 2006; Coscia et al., 2012) and reagent solution flow in enhanced recovery of gold from ore heaps (Rucker et al., in press). A number of techniques have been proposed for the inversion of time-lapse data (Mitchell et al., 2011), including independent inversions (Cassiani et al., 2006), using the ratio of the data from the initial and later data sets (Daily et al., 1992), using the difference in the apparent resistivity values (LaBrecque and Yang, 2001), simultaneous inversion (Hayley et al., 2011), and incorporating the
temporal data and model directly into the least-squares regularization method (Kim et al., 2009; Loke and Dahlin, 2011). The inversion methodology by Loke and Dahlin (2011) uses the following equation:

\[ J^T i R d J_i + \lambda_i W^T R_m W + \alpha_i M^T R_m M_i \Delta r_i = J^T i R d g_i - \lambda_i W^T R_m W + \alpha_i M^T R_m M_i r_i - 1 \]  

(3)

where \( M \) is the difference matrix applied across the time models with only the diagonal and one sub diagonal elements having values of 1 and -1, respectively. \( \alpha \) is the temporal damping factor that gives the weight for minimizing the temporal changes in the resistivity compared to the model roughness and data misfit. While time-lapse surveys can be conducted using standard equipment used in 2-D and 3-D surveys, a number of dedicated automatic monitoring systems with permanently installed cables and electrodes have been developed.

As an example of a large 4-D resistivity monitoring scenario, consider the site presented in Fig. 6. Fig. 6A shows the location map of a gold mine where a survey was conducted to map reagent flow injected into low grade ore for enhanced recovery after conventional surface leaching (Rucker et al., in press). The resistivity was to be used to help optimize injection parameters, such as pressure, rate, and duration of the injection. There is a total of 150 electrodes arranged in a radial pattern on the surface around the injection well and along six boreholes (Fig. 6B). Six nearby injection wells were also used as long electrodes. A total of 780 sets of measurements, or snapshots, were made over an eight day period. Fig. 7 shows the results from one set of measurements made on the last day after the injection of the reagent into a well (marked in red on Fig. 7, adapted from Rucker et al., in press). The movement of the reagent is illustrated as 3-D rendered transparent volumes showing regions with 3, 6 and 12\% decrease in the resistivity. The movement of the reagent was also tracked in real-time by monitoring the current and voltage at the subsurface electrodes.

This field example also provides a glimpse of the tremendous progress made by the geoelectrical method over the past 25 years, from mainly simple 1-D models with flat layers up to the late 1980’s to present-day 4-D models in an area with significant surface topography with complex variations in both space and time.

4. Practical applications

This section gives a brief outline of the use the geoelectrical imaging method in various fields where it plays an important economic role.

4.1. Mineral exploration

Multi-dimensional resistivity surveys, usually in conjunction with I.P. measurements, are widely used in base and precious metals exploration due to the complex geological environments encountered. The electrical surveys are frequently conducted after reconnaissance aeromagnetic and airborne EM surveys have identified specific areas of interest. The introduction of 2-D and 3-D data computer inversion techniques has greatly improved data interpretation for both new surveys and historical data (Collins, 2009; Mutton, 2000; Nabighian and Asten, 2002). While massive sulfide ore deposits show a distinct resistivity and I.P. anomaly, the I.P. data are the more diagnostic tool in the exploration for disseminated ore in a geochemically reduced state. In precious metals exploration, where conductive minerals occur as accessory minerals, the I.P. information gives useful information on the shape of the orebody while the resistivity gives more information about the general geology of area (Guo et al., 1999; Spitzer and Chouteau, 2003). Three-dimensional resistivity and I.P.
surveys are now widely used for such surveys, where efficient field techniques have been developed to cover wide areas rapidly and to reduce EM coupling effects (White et al., 2001). Resistivity surveys have played an important role in the exploration of deeply buried uranium deposits in Canada’s Athabasca Basin (Legault et al., 2008). The search for deeper metalliferous deposits has also led to developments in more powerful field instruments (Eaton et al., 2010; Goldie, 2007) some of which includes signal processing functions to improve the measurement of complex resistivity signals (Chen et al., 2009; Matthews and Zonke, 2003).

Other mineral resources where electrical methods have been used include graphite (Ramazi et al., 2009), bauxite (Bi, 2009), nickel (Robineau et al., 2007), chromite (Frasher, 2009; Mohanty et al., 2011), manganese (Murthy et al., 2009), boron (Rayak and Leyla, 2012), coal (Singh et al., 2004), and iron ore (Butt and Flis, 1997). Resistivity surveys are also widely used to map shallow oil sand deposits (Bauman, 2005), while there is ongoing research in use of resistivity and I.P. surveys for deeper conventional hydrocarbon resources through a detailed analysis of subsurface structural components. Mapping the hydrostratigraphy, that is using resistivity to define units that are important to hydrogeological analyses, has been effectively conducted by Ismail et al. (2005), Clifford and Binley (2010) and Mastrocicco et al. (2010). A nationwide mapping of the groundwater resources in Denmark has been carried out using EM and electrical methods (Auken et al., 2006) that is probably the first of its kind.

A growing body of research has emerged around investigations for obtaining hydraulic parameters with resistivity, including saturated hydraulic conductivity for groundwater systems and parameters that describe soil moisture characteristic curves that fit the van Genuchten, Brooks Corey, or other well known functions. For this work, heretofore referred to as hydrogeophysics, several strategies for integrating water flow and geophysical modeling have been taken that includes sequential assessments (e.g., Daily et al., 1992; French and Binley, 2004; Kemna et al., 2002; Park, 1998; Sandberg et al., 2002), joint modeling (Chen et al., 2006; Linde et al., 2006a,b), and fully coupled inverse modeling (Hinnell et al., 2010; Lehikoinen et al., 2009; Rucker, 2009). Ferré et al. (2009) provide coherent definitions for each type of these hydrogeophysical analyses. The advantage of these approaches is that hydrological inverse modeling on a limited number of point measurements is ill-posed due to an inadequate spatial measurement resolution or low information content of the measured signal. Electrical resistivity measurements, or any geophysical measurement sensitive to hydrogeological variables, have the ability to

4.2. Hydrological

Applying the electrical resistivity method to solve hydrological problems has ranged from the regional scale of water resource exploration to the local scale for estimating hydraulic conductivity. Early work for hydrologically-based electrical resistivity problems focused on locating resources for exploitation with one-dimensional vertical electrical soundings (Patra and Bhattacharya, 1966; Zohdy and Jackson, 1969). Soon thereafter, several noticed that hydraulic parameter estimation was feasible by combining pump tests with resistivity information from the VES to formulate regression models at co-located measurement locations (Sri Niwas and Singhal, 1985). This methodology is still in use today for extremely deep aquifers (e.g., Tizro et al., 2010) and in many rapidly developing parts of the world (e.g., Asfahani, 2012; Chandra et al., 2011; Ekwe et al., 2010; Khalil, 2010) where access to multi-channeled resistivity systems is limited. The popularity and success of the joint physical characterization of aquifers can likely be attributed to similar support voltages over which these measurements are conducted and the analogous flow characteristics of water and electrons within the most transmissive portions of rocks and soils.

Site complexity can also be studied effectively with resistivity to define aquifer geometry, geological structure, and hydrostratigraphic sequences. Depth to bedrock studies is a classical example of using resistivity to help define geometry. For example, Zhou et al. (2000) examined the case of overlying soil thickness above a limestone karst system. Griffiths and Barker (1993), Beauvais et al. (2004), and Hirsch et al. (2008) also examined the bedrock topography for both resistive and conductive basements. Rayner et al. (2007), Gélis et al. (2010), and Schütze et al. (2012) explored aquifer architecture through a detailed analysis of subsurface structural components. Mapping the hydrostratigraphy, that is using resistivity to define units that are important to hydrogeological analyses, has been effectively conducted by Ismail et al. (2005), Clifford and Binley (2010) and Mastrocicco et al. (2010). A nationwide mapping of the groundwater resources in Denmark has been carried out using EM and electrical methods (Auken et al., 2006) that is probably the first of its kind.

Fig. 6. (A) Location map of the Cripple Creek and Victor gold mine, Central Colorado, showing injection area within the mine’s boundary. (B) Map showing injection wells (stars), surface electrodes (dots), and borehole electrode arrays (diamonds).
provide information with a spatial resolution that is much higher than hydrological measurement methods alone (Huisman et al., 2004). Secondarily, the tomographic model produced from resistivity may be constrained to produce features that are consistent with hydrogeological analyses.

4.3. Environmental

Borrowing the description of environmental geophysics from Reynolds (2011), environmental applications for resistivity include those that aim to investigate near surface bio-physico-chemical phenomena having significant implications for environmental management. Regarding this definition, many resistivity projects have examined the release of contaminated waters to both the soil and groundwater, where high ionic strength solutions provide a sufficient contrast with the host environment for mapping the extent of a subsurface plume. The focus on environmental applications has produced a very large body of work from which to pull and covers a broad spectrum of test cases. Over the past decade, the newer directions of the resistivity method for mapping the spatial aspects of contaminated ground have been to detect even more subtle resistivity contrasts in highly complex environments, increasing electrode coverage by upscaling their numbers in hard to reach areas, accommodating as much a priori information as possible into the inverse modeling algorithms, and developing petrophysical relationships that allow the transformation of bulk resistivity to a variable of state (such as contaminant concentration).

Classical applications of electrical resistivity to plume mapping can be traced to solid or liquid waste repositories (e.g., landfills, refineries, petrol stations, holding ponds, waste storage facilities), groundwater

Fig. 7. Inversion results from data extracted during the last day of injections at 34 and 27 m. The results are presented as percent change from background conductivity (positive indicating an increase in conductivity). The three transparent bodies of the 3D rendered plots represent 3, 6, and 12% change from background. The injection zone is marked by a gray cylinder. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

* Distance data are in meters
contamination from salt-laden waters originating from industrial, mining, and agricultural processes (e.g., brine pits, road salt or fertilizer run off, tailing piles, animal feed lots), and coastal salt water intrusion mapping. Examples for leachate emanating from a landfill are plentiful in the published literature, but a few recent studies include those by Bernstone et al. (2000), Chambers et al. (2006), and Clément et al. (2010). Agriculturally based contamination case studies have included nitrate infiltration from nonpoint source releases through the overuse of fertilizers (Boadu et al., 2008) and animal waste at feedlots (Sainato et al., 2012). Hydrocarbon-based spills have also been shown to be interesting targets, as a resistive body may develop from free product (Atewkanwa and Atewkanwa, 2010) or a conductive body from the degradation of chlorinated solvents (Sauck, 2000). Some of the more intense targets have been discovered around nuclear waste disposal sites (Rucker et al., 2009a) and mine tailings (Martín-Crespo et al., 2011; Rucker et al., 2009b), where ratios of resistivity from background conditions to contaminated ground can easily reach 10,000:1. A similar application with large resistivity contrasts is saline water intrusion mapping in coastal areas (de Franco et al., 2009; Wilson et al., 2008). Several researchers have used the resistivity method to examine a reduction in contaminant loading from cleanup activities and remediation (Bentley and Gharibi, 2004; Chambers et al., 2010; Slater and Binley, 2003).

The examples above discuss environmental applications of resistivity from unplanned releases, whereby contaminants are accidentally released or the consequences of release were not meant to be as severe. An alternative realm of study is the planned release of an electrolytic tracer to more fully understand physical and chemical processes within porous media. Early work by Fried (1975), White (1988), and Lile et al. (1997) used resistivity imaging during salt water injections to understand groundwater flow directions, velocities, and mechanical dispersion. Presently, the practice is quite common in open ground (e.g., Cassiani et al., 2006; Monego et al., 2010; Robert et al., 2012; Wilkinson et al., 2010b) and within small sand tanks and columns (Lekmine et al., 2010; Slater et al., 2002).

The large number of test cases available in the literature is a testament to the versatility of resistivity to solve many different types of environmental problems, from the large catchment scale (Robinson et al., 2008) to characterization of pore-scale transport processes (Singha et al., 2008). Complex industrial sites also have a particular subset of novel solutions for acquiring data, including a high density of borehole arrays (Johnson et al., 2010), push technology (Pidlisceky et al., 2006), and the use of wells as long electrodes (Rucker et al., 2010, 2011a, 2012). Finally, to accommodate all spatial and temporal scales necessary to capture the relevant dynamics of these specialized problems, both high capacity acquisition hardware (e.g., Kuras et al., 2009; Rucker et al., in press) and software (Loke et al., in press) are available to increase the resolution of the method and highlight even more subtle features.

4.4. Engineering

Resistivity imaging is widely used across an enormous range of engineering applications, including the investigation and monitoring of made or artificial ground, and structures such as foundations, tunnels, earthworks and landfills, soil stability, as well as anthropogenic problems associated with mining related activities.

Spatial information provided by resistivity imaging has proved to be effective in characterizing heterogeneous made ground, in terms of thickness and internal and external geometry (Guerin et al., 2004). For foundations, it has been applied to pre-installation ground assessment (Soupis et al., 2007), investigation of existing foundations (Cardarella et al., 2007), and the monitoring of foundation stabilization procedures (Santaratro et al., 2011). It has been used to predict ground conditions ahead of tunneling operations (Danielsen and Dahlín, 2009) to differentiate between poor (weathered) and good (unweathered) quality rock. Earthwork investigations employing resistivity imaging have been used to characterize (Bedrosian et al., 2012; Kim et al., 2007; Minsley et al., 2011; Oh, 2012) and monitor (Sjödahl et al., 2008, 2009, 2010) dams, and assess the condition of rail (Chambers et al., 2008; Donohue et al., 2011) and road (Fortier et al., 2011; Jackson et al., 2002) embankments. Mine related engineering applications include in-mine imaging during working (van Schoor, 2005; van Schoor and Binley, 2010), as well as the detection and characterization of old abandoned mine workings (Chambers et al., 2007; Kim et al., 2006; Maillol et al., 1999; Wilkinson et al., 2005, 2006a).

Resistivity imaging is now a well-established technique for landslide studies (Jongmans and Garambois, 2007), as it provides rapid and lightweight means of acquiring spatial information related to ground structure, composition, and hydrogeology on unstable slopes. Landslide investigations are dominated by 2-D resistivity imaging with numerous recent examples of the use of the technique for structural characterization in hard-rock settings (Bekler et al., 2011; Jomard et al., 2010; Le Roux et al., 2011; Mignon et al., 2010; Panek et al., 2010; Socco et al., 2010; Tric et al., 2010; Zerathe and Leborg, 2012) and soft rock settings (Bievre et al., 2012; Chang et al., 2012; de Bari et al., 2011; Erginal et al., 2009; Grandjean et al., 2011; Hibert et al., 2012; Jongmans et al., 2009; Leborg et al., 2010; Piegarì et al., 2009), and hydrogeological investigations (Bievre et al., 2012; Grandjean et al., 2009; Jomard et al., 2010; Lee et al., 2012; Travelli et al., 2012; Yamakawa et al., 2010). Three-dimensional resistivity imaging, while less commonly applied, has also been used to investigate the internal structure and hydrogeological regimes associated with landslides (Chambers et al., 2011; Di Maio and Piegarì, 2011, 2012; Heincke et al., 2010; Leborg et al., 2005; Udphaya et al., 2011). A class of landslide hazard for which resistivity imaging has proved to be particularly applicable is quick clay, which is prevalent across parts of Scandinavia and North America. Resistivity imaging has been used to locate and map quick clay formations due to the higher resistivity exhibited by quick (leached) compared to non-quick (unleached) formations (Donohue et al., 2012; Lundstrom et al., 2009; Solberg et al., 2008, 2012).

A number of studies describe the use of resistivity imaging for detecting open cavities (Deceuster et al., 2006; Nyquist et al., 2007; Zhu et al., 2012), collapsed or suspected sinkholes (Ezersky, 2008; Gutiérrez et al., 2009; Valois et al., 2011), and caves (Schwartz et al., 2008) that may affect the structural integrity of a building or may pose a safety hazard. As a target, these features can be either conductive for the water- and clay-filled cavities, or resistive for air-filled cavities (Smith, 1986). Electrical resistivity lines placed either on the surface or in boreholes have been used to help find and map these features quite successfully.

Others have used resistivity to specifically understand geotechnical properties of engineering materials. Unfortunately, there is no direct causative relationship between electrical resistivity and, say, rock strength. Indirectly, however, the resistivity value can be dependent upon jointly influencing parameters that comprise certain hydrogeological (e.g., Boadu, 2011; Boadu and Owusu-Nimo, 2010) or geomechanical attributes of rock, such as porosity, void ratio, water content, cementation, or composition. The Archie equation (Archie, 1942) shows that for fully saturated media, an increase in porosity causes the resistivity to decrease exponentially. In cases of sedimentary rock, the porosity exponent has been related to cementation or tortuosity through the pore networks (Schon, 1996). Based on these influencing parameters that link porosity to both elastic modulus (e.g., Kahrman and Alber, 2006) and electrical resistivity, some have constructed simple correlations between a mechanical parameter and a resistivity for co-located measurements. This was the method applied by Braga et al. (1999), Oh and Sun (2008), and Sudha et al. (2009) when presenting blow count from standard penetration tests to an inverted resistivity value, when acquired as one-dimensional vertical electrical soundings or two-dimensional transects. Cosenza et al. (2006) used resistivity to create a scatter
plot of co-located data with the cone resistance and found logical groupings of data associated with the specific lithology from which the data were collected.

4.5. Agriculture and soil science

Resistivity, and in particular its reciprocal, electrical conductivity (EC), have played an important role in the fields of agriculture and soil science for many years as they are among the most useful and easily obtained spatial properties of soil that influence crop productivity (Corwin and Lesch, 2003, 2005; Samouelian et al., 2005). The sensitivity of both parameters to soil moisture content, salinity and clay fraction makes them ideal candidates for mapping and evaluating the properties of agricultural land, for characterizing field variability in precision agriculture and for monitoring of hydrological processes and soil performance in terms of nutrient cycling and storage. Traditionally, high-resolution lateral mapping of resistivity or soil EC at discrete depths of investigation (Dabas, 2009; Dabas et al., 2012; Gebbers et al., 2009) has been favored over resistivity imaging in the strict interpretation of the term, and a range of measurement techniques based on inductively, galvanically and capacitively coupled sensors is available (Alfred et al., 2006; Dabas and Tabbagh, 2003).

Direct-current resistivity imaging (2-D and 3-D) has been successfully applied to characterize the tillage layer (Basso et al., 2010; Besson et al., 2004; Seger et al., 2009), to detect soil cracking at small scales (Samouelian et al., 2004), to estimate and monitor soil moisture in the root zone and monitor plant uptake (Celano et al., 2011; Nijland et al., 2010; Schwartz et al., 2008), to assess soil water deficit (Brunet et al., 2010), to monitor water percolation and optimize irrigation patterns (Greve et al., 2011; Kelly et al., 2011), to map and quantify root biomass (al Hagrey, 2007; Amato et al., 2009; Rossi et al., 2011), to characterize soil contamination and monitor remedial treatment (West et al., 1999), to define management zones on farms, plantations and vineyards (Morari et al., 2009), to investigate soil weathering profiles (Beavais et al., 2004), and to establish integrated 3D soil-geology models (Tye et al., 2011). Resistivity imaging is also used extensively in the related field of geoforensics (Pringle et al., 2008; Ruffell and McKinley, 2005).

4.6. Archeology and cultural heritage

In terms of its historical development, the ERT method is arguably very closely associated with archeological investigation (Noel and Xu, 1991). For archeological purposes however, the lateral mapping of resistivity (or more typically earth resistance, i.e. the response of a fixed–geometry four-electrode array inserted into the soil) has long been dominant amongst electrical methods for characterizing large archeological sites and discriminating buried man-made structures (Gaffney, 2008). More recently though, detailed 2-D and 3-D resistivity imaging have become increasingly popular amongst archeologists as the method permits closer scrutiny of archeological targets prior to excavation, for example by volumetric analysis and visualization.

Successful archeological applications of DC resistivity imaging include the non-destructive characterization of mounds and tumuli (Griffiths and Barker, 1994; Papadopoulos et al., 2010; Wake et al., 2012), the investigation of multilayered human settlements (Berge and Drahor, 2011a,b), the mapping of buried walls, voids and passageways (Leucci et al., 2007; Negri and Leucci, 2006; Orfanos and Apostolopoulos, 2011), the imaging of ancient city walls and preeminent monuments (Tsokas et al., 2011; Tsourlos and Tsokas, 2011), the detection of tombs and the definition of their geometry (Elwaseif and Slater, 2010; Matias et al., 2006), the detection of archeological structures buried under exceptionally thick soil (Drahor, 2006), the investigation of previously excavated and then backfilled features (Sambuell et al., 1999), the improved understanding of geological constraints on archeological sites (Ercoli et al., 2012; Similox-Tohon et al., 2006), and the comprehension of historic workflows and manufacturing processes (Leopold et al., 2011). Seafloor archeological applications of marine resistivity imaging have also been reported (Passaro, 2010).

A promising field of application is “rescue archeology”, which comprises archeological survey and excavation carried out in areas threatened by, or revealed by, construction or other land development. This type of archeological investigation must be carried out at speed; hence resistivity imaging proves to be a useful tool to support these surveys (Batayneh, 2011; Loperte et al., 2011). Cultural heritage preservation is another related field where the benefits of resistivity imaging have been recognized (Mol and Preston, 2010). Its use has been frequently reported for the structural assessment and restoration of historical buildings built over more ancient structures (Capizzi et al., 2012; Dabas et al., 2000; Di Maio et al., 2012; Tsokas et al., 2008).

4.7. Waterborne resistivity

Electrical resistivity investigations applied in marine environments can be traced back to at least the mid-1930s (Schlumberger et al., 1934) where the method was used to map limestone outcrops in the Caspian Sea and to determine the depth to bedrock in Algiers harbor (Corwin et al., 1985). Since then, applications for waterborne resistivity have spanned a wide array of problems that mostly mimic terrestrial applications, but with a few that are unique to the marine setting. For example, geological mapping, including bedrock geometry, structure, lithology, and hydrostratigraphy is a rather typical application of both land and waterborne resistivity methods (e.g. Rinaldi et al., 2006; Rucker et al., 2011b). Submarine groundwater discharge (SGD), on the other hand, is a particular area of study for off-shore resistivity characterization. SGD describes how freshwater may move from aquifers to the sea and several large scale projects have been conducted to observe these interactions (Day-Lewis et al., 2006; Henderson et al., 2010; Swarzenski et al., 2006, 2007).

The acquisition of resistivity in aquatic environments can be conducted at the water surface with floating electrodes (e.g. Hatch et al., 2010; Kelly et al., 2009; Song and Cho, 2009) or submerged at the floor (Toran et al., 2010), with both strategies typically used in conjunction with continuous resistivity profiling (CRP). CRP involves towing a multi-cored cable behind a vessel and using one pair of current transmitting electrodes and multiple pairs of potential measurement electrodes. The rate at which data are acquired is usually slower for the submerged array (Corwin et al., 1985), but typical acquisition rates may be 3–5 km/h (see Snyder and Wightman, 2002). The choice of floating or submerged electrodes depends on the depth of the water column, with very thin or very thick water columns using submerged electrodes and the intermediate range opting for floating electrodes (Loke and Lane 2004) recommend that floating electrodes be used when the water column is no greater than 25% of the total depth of investigation and Lagabrielle (1983) discusses the sensitivity of both cases. In extremely shallow situations involving streams, it may be more advantageous to use fixed submerged arrays instead of CRP to avoid damage to the cable.

Several commercial instruments are available for acquiring CRP data for marine environments, which primarily need the ability to automatically log voltage data for a given electrode array. For freshwater environments, where the resistivity values of the water column are relatively high, low powered systems (200–400 W) can be used quite effectively. In highly conductive seawater, higher powered systems (> 1kW) are recommended to overcome the noise. Corwin et al. (1985) state that 10 A of current was sufficient to overcome noise in seawater for a submerged Schlumberger array with AB/2 = 316 m. Rucker et al. (2011b) used a low powered system in the resistive waters of the Panama Canal with a floating dipole array and an electrode spacing of 15 m, while Kelly et al. (2009) used non-uniform spacings
ranging 0.5 to 128 m. in a survey along the Namoi River in Australia. Butler (2009) lists other examples of instrumentation power versus electrode geometry and environment. Most modern equipment also has the ability to accept GPS data to help georeference each measurement.

Data processing of the resistivity profiles typically involves two-dimensional inversion and investigating conductive or resistive bodies along the transect. Constraints, such as the bathymetry and conductivity of the water, can be added to the inversion to help resolve issues at the water–rock interface. Provided the data are sufficiently georeferenced, multiple individual profiles can be interpolated at off-line locations to produce quasi 3-D volumes. Recently, true 3-D inversion models of marine resistivity data collected over a series of parallel profiles have been generated and Mansoor and Slater (2007) demonstrate how repeated measurements over the same grid can produce high quality time-lapse information of a shallow wetland. Rucker and Noonan (in press) demonstrate for long subparallel lines that 3-D resistivity modeling can still be conducted efficiently if the numerical grid generated for the forward model is distinctly separate from the inverse model grid. A meandering trajectory does not lend itself well to inverse models that strictly adhere to grids generated from each unique electrode position. Fig. 8 presents an example from the survey by Rucker and Noonan (in press) in the Panama canal. Fig. 8A shows the location of the survey and Fig. 8B details the acquisition within the canal as well as the grid used to conduct the 3D model. Cell sizes were a uniform 30 m × 30 m with 2 m layering to a depth of 32 m. The water column ranged from 15 to 19 m with a resistivity of 67 Ω.m. Fig. 8C shows the results of the inverse 3-D modeling as horizontal slices. The upper two subplots represent the water column and the lower subplots show the distribution of rock properties associated with hard (high resistivity) or soft (low resistivity) material.

5. Special topics

In this section, a brief overview of more recent developments is given. All of the techniques have been tested in field surveys, while most are commercially available.
5.1. Cross-hole ERT

In order to improve the resolution of resistivity images at depth, electrodes are often placed in boreholes (Perri et al., 2012). Measurements are then made with various quadrupole combinations of current and potential electrodes, either in the same hole (Slater et al., 2000), between the hole and the surface (Tsourlos et al., 2011) or between pairs of holes (Zhou and Greenhalgh, 2000). The design of surveys for cross-hole imaging has traditionally not been as widely researched as for surface investigations, although recent studies have largely redressed this imbalance. To achieve acceptable image resolution between a pair of boreholes, the separation of the holes should not be more than about 0.75 times the borehole array length (LaBrecque et al., 1996b). The layout of the boreholes can be regular (LaBrecque et al., 1996; Wilkinson et al., 2006a) or irregular (Chambers et al., 2007; Tsokas et al., 2011) depending on ground conditions and the presence of buildings or infrastructure. Measurements are typically made between pairs of boreholes (“panels”) and either inverted in 2-D for individual panels (Deceuster et al., 2006) or in 3-D for combinations of panels (Nimmer et al., 2008; Wilkinson et al., 2006a). The types and combinations of quadrupoles used to measure the data have been studied in terms of maximizing signal-to-noise and image resolution (al Hagrey, 2011; Goes and Meekes, 2004; Slater et al., 2000; Zhou and Greenhalgh, 2000).

Automated survey design algorithms have also been applied to the borehole ERT problem (al Hagrey, 2012; Wilkinson et al., 2006a). Since it is more difficult to determine accurate positions for borehole electrodes than surface electrodes, consideration must also be given to the effects of random and systematic offsets in electrode positions and deviations of the boreholes from their assumed locations and direction (Oldenborger et al., 2005; Wilkinson et al., 2008; Yi et al., 2009).

Achieving and maintaining good galvanic contact with the ground are also more challenging in boreholes than with surface arrays. In the saturated zone, most forms of completion will permit contact with the electrode, including native backfill (Tsokas et al., 2011), metal casing (Osiensky et al., 2004), and slotted plastic casing (Wilkinson et al., 2006a). In the vadose zone, backfill with bentonite or similar conductive material is desirable to maintain electrical contact (Wilkinson et al., 2010b). However, most forms of completion change the electrical properties of the ground in the near vicinity of the electrodes, and can therefore have a pronounced effect on the measurements. The effects of metal cased boreholes (Schenkel and Morrison, 1994; Singer and Strack, 1998), grouted boreholes (Denis et al., 2002), and fluid-filled boreholes (Nimmer et al., 2008; Osiensky et al., 2004) have all been analyzed in detail, allowing the effects of boreholes on the resulting inverted images to be understood quantitatively. It is further possible to incorporate a borehole model directly in the inversion to remove these effects in 2.5-D (Sugimoto, 1999) and 3-D (Doetsch et al., 2010).

5.2. Mobile systems and capacitive resistivity imaging

Continuous data acquisition systems for waterborne surveys were described in an earlier section of this paper. Similar systems for land surveys have also been developed. Some systems use cylindrical steel electrodes based on an in-line array geometry (Sörensen, 1996), while others use spiked wheels to achieve continuous galvanic contact with the soil (Dabas, 2009; Panissod et al., 1998). Capacitively coupled systems are used in areas with very resistive surface materials (e.g. dry or frozen ground) or paved surfaces. These instruments use an oscillating, non-grounded electric dipole to generate current flow in the ground and a second similar dipole to measure the resulting potential distribution at the ground surface (Kuras et al., 2006). There are two major configurations for this type of instrument. The first configuration (line antenna type) uses cylindrical transmitters and receivers that are towed behind an operator (Fig. 9A). It gives measurements with typical depths of investigation of 1 to 20 m that are comparable to the galvanically coupled in-line dipole–dipole array (Møller, 2001). However, line antenna data do not fulfill the point source assumption of DC resistivity theory, and particular care must therefore be taken when interpreting such datasets (Neukirch and Klitzsch, 2010). The second type (electrostatic quadrupole) uses flat metallic conductors in an equidistant dipole–dipole configuration (Panissod et al., 1998; Soufachede et al., 2010) and has maximum survey depths of up to a few meters (Fig. 9B). 2-D and 3-D surveys with dense lateral coverage can be rapidly conducted with these systems, and it has been shown that DC resistivity methodology and inversion schemes can be usefully applied to such datasets (Kuras et al., 2007). The term “capacitive resistivity imaging (CRI)” has become synonymous with this approach. Mobile arrays have traditionally employed a limited number of dipoles and associated 2-D and 3-D models are therefore restricted in terms of their spatial resolution. Moreover, these arrays operate primarily at the meter scale. In a more recent development, Kuras et al. (2012) describe novel multi-sensor CRI instrumentation, which is applied to the 4-D monitoring of rock-freezing experiments in the laboratory. This methodology holds promise for applications of ERT in cryospheric science, such as the monitoring of rocks and soils under permafrost conditions (De Pascale et al., 2008; Hauck and Kneisel, 2006; Krautblatter et al., 2010).

5.3. Unconventional electrodes

Metal stakes are commonly used as the electrodes in resistivity surveys. While steel electrodes are widely used, other types of metals (and graphite) have also been used (LaBrecque and Daily, 2008; Lu and Macnae, 1998). Aluminum foil covered with soil soaked with salt water is used as current electrodes when a current (1 to 20 A) is needed (Ward, 1990). In areas where it is difficult to insert a stake electrode (such as paved ground), flat-base (or plate) electrodes have been used (Athanassiou et al., 2007; Tsokas et al., 2008). Galvanic contact with the ground is achieved using an electrically conductive gel or mud at the base of the electrode. Non-polarizable electrodes (Reynolds, 2011) are widely used as the potential electrodes in I.P. surveys to reduce SP noise, although there has been recent progress in using conventional metal electrodes (Dahlin and Leroux, 2012) which are more convenient to use with multi-electrode systems. In modeling the potentials, the electrode is usually assumed to be an ideal point. The effect of the finite size of the electrode is small if the ratio of the electrode length to the electrode spacing is less than 0.2 (Rücker and Günther, 2011).

In some areas, the existence of widespread subsurface infrastructure can make the detection of subsurface targets by normal surveys with electrode on the ground surface difficult. The use of existing metallic wells as long electrodes can significantly improve the detection of targets in such areas (Rucker et al., 2010, 2011a, 2012). Long electrodes are wells grounded to the earth, extend to the target of interest, are already in existence, and can continue to operate in a normal capacity during imaging. Logistically, the wells are connected to the resistivity acquisition system through a dedicated wire, which is connected to the innermost casing that extends the deepest into the earth. Care must be taken to ensure (1) a secured contact between the wire and well, which usually involves cleaning the steel casing with a wire brush, and (2) the well is electrically isolated from other metallic infrastructure such as pipes that may be used to carry fluid. The numerical models accommodate the long electrode by assigning those mesh cells representing the well with very low values. Synthetic studies, pilot scale field examples, and full scale field examples have demonstrated that long electrodes can reproduce the lateral extents of conductive targets with reasonable fidelity, but with significant loss of vertical resolution. Vertical resolution can be enhanced by combining long electrodes with a large number of short electrodes on the surface (Zhu and Feng, 2011), combining
vertical long electrodes with horizontal long electrodes, i.e., pipes (Ramirez et al., 2003), by using inclined wells (Hatanaka et al., 2005), or through optimized arrays (Rucker, 2012).

5.4. Automatic monitoring systems

Increased interest in monitoring instrumentation has accompanied rapid developments in the application of geoelectrics to process related problems in fields such as hydrogeophysics (e.g. Rubin and Hubbard, 2005) and landslide and slope stability studies (e.g. Jongmans and Garambois, 2007). Automation of resistivity data acquisition, using PC or microprocessor controlled monitoring systems for remote deployment with permanently installed electrode arrays, has facilitated monitoring at the spatial and temporal resolution required to capture small-scale transient events associated with these types of applications. Specific applications include: landslides (Niesner, 2010; Supper et al., 2008; Wilkinson et al., 2010a); dams (Sjodahl et al., 2009, 2010); landfill (Johansson et al., 2011); frozen ground (Hilbich et al., 2011); CO2 storage (Kiessling et al., 2010); tracer tests (Coscia et al., 2011; Oldenborger et al., 2007a; Wilkinson et al., 2010b); and leak detection (Calendine et al., 2011; Daily et al., 2004).

Approaches to system development have included both the adaption of commercial resistivity survey instrumentation for monitoring purposes (Daily et al., 2004; Hilbich et al., 2011; Johansson et al., 2011; Kiessling et al., 2010; Sjodahl et al., 2009, 2010), and the development of purpose-built resistivity monitoring systems (Kuras et al., 2009; Labrecque et al., 2004; Ogilvy et al., 2009; Rucker et al., in press; Supper et al., 2008; Wilkinson et al., 2010a,b). Monitoring installations

Fig. 9. Capacitively coupled systems using (A) cylindrical transmitter and receiver (line antenna type) and (B) flat metallic plates. British Geological Survey (c) NERC 2013.
are becoming increasingly sophisticated, and now incorporate telemetric control and data transfer, and local power generation through wind, solar, and fuel cell technology (Hilbich et al., 2011; Supper et al., 2008; Wilkinson et al., 2010a). With the automation of data acquisition and the generation of very large data volumes, systems are also being developed to manage the entire workflow, including scheduling of data collection, retrieval and storage, quality assessment and inversion (Chambers et al., in press; LaBrecque et al., 2004; Ogilvy et al., 2009).

5.5. Optimized survey design

Most surveys are carried out with conventional arrays such as the dipole–dipole, pole–dipole, Wenner, Wenner–Schlumberger and multiple-gradient arrays (Dahlin and Zhou, 2004; see Fig. 3). In recent years, there has been significant development of algorithms to automatically determine non-conventional electrode configurations that will produce better image resolution while using the same number of data points (Stummer et al., 2004; Wilkinson et al., 2006b). A field example comparing the results of a dipole–dipole and an optimized array of the same size is shown in Fig. 10. The geological interfaces are more clearly resolved in the optimized image.

Several different approaches have been proposed to design arrays that maximize the image resolution including: reconstructing comprehensive data sets from a linearly independent complete subset (Blome et al., 2011; Lehmann, 1995; Zhe et al., 2007); maximizing a sum of Jacobian sensitivity matrix elements (Furman et al., 2004, 2007); maximizing cumulative sensitivity while minimizing mutual current distributions (Nenna et al., 2011); maximizing a sum of model resolution matrix elements (al Hagrey, 2012; Loke et al., 2006b; Stummer et al., 2004; Wilkinson et al., 2006b, 2012a); minimizing an average measure of the point spread function (Loke et al., 2010b); and maximizing the determinant of the normal matrix (Coles and Morgan, 2009). Most of the optimization algorithms are based on sensitivity and current-flow distributions for homogeneous resistivity models. Although this assumption might be thought to limit the applicability of the optimized surveys, it has been demonstrated that incorporating prior estimates of the resistivity model into the design algorithms (Nenna et al., 2011) does not significantly improve the image resolution (Stummer et al., 2004; Wilkinson et al., 2012b).

For optimized arrays to be useful in practice, other design constraints and goals must often be considered in addition to maximizing the image resolution. These include incorporating error estimates in the resolution calculation; minimizing electrode polarization errors; and making efficient use of multiple measurement channels for both normal and reciprocal data acquisition. Recent studies have addressed many of these issues: Blome et al. (2011) for complete pole–dipole data sets, and Nenna et al. (2011) and Wilkinson et al. (2012a) for optimized four-pole data sets. Although the optimization algorithms developed so far have focussed on the 2-D problem, in principle the extension to 3-D is straightforward and limited only by computational resources. Preliminary investigations using general purpose GPUs to accelerate the calculations (Loke et al., 2010b) have shown that 3-D optimization is feasible for subsets of measurement types (Rucker and Loke, 2012).

6. Limitations of the resistivity method

6.1. Non-uniqueness and resolution

The inverse resistivity problem has a unique solution for 1-D, 2-D and 3-D resistivity distributions within a boundary (Friedel, 2003), but only under strict conditions where the voltage and current distributions are known continuously and precisely over the boundary for a complete set of current injection patterns. In practice, resistivity inversion is ill-posed and non-unique due to only being able to use a finite number of electrodes covering part of the surface. This implies that more than one resistivity model will produce responses consistent with the observed data to the limits of the data accuracy (Hoffmann and Dietrich, 2004). Regularization is used, often in the form of a smoothing matrix (Loke et al., 2003), to enforce uniqueness without sacrificing too much resolution. However regions of the inverted image where the model resolution is lower (see Optimized survey design section) will depend more strongly on the type of constraint used (Oldenborger et al., 2007b; Oldenburg and Li, 1999). The inverse images will therefore only accurately reflect the true subsurface resistivity if the regularization constraints are realistic. Typically the image resolution diminishes exponentially with the distance from the electrodes. If the resolution needs to be maintained with depth for surface surveys, the surface measurements can be supplemented by surface-to-hole or cross-hole measurements (see Cross-hole ERT section).

6.2. Data quality

Measured data, and the resulting resistivity images (LaBrecque et al., 1996a), are subject to error from a variety of sources including that introduced by the measurement device, poor electrode contact (usually identified through high contact resistances) or electrode polarization, and other indeterminate external effects (Dahlin, 2000; Merriam, 2005; Wilkinson et al., 2012a). These issues are addressed through the appropriate selection and conditioning of electrodes to reduce contact resistance (also see Unconventional electrodes section), by using appropriate filters (including reciprocal error analysis) prior to inversion (Ferahtia et al., 2009; Zhou and Dahlin, 2003), and through employing measurement sequences that reduce the influence of electrode polarization. In practice, polarization can be reduced by ensuring adequate time between using an electrode to pass current and measure potential (Wilkinson et al., 2012a).

6.3. Electrode position

Electrode position is usually assumed to be known and fixed for the purposes of geoelectrical survey and monitoring. However, for difficult ground conditions such as steep or heavily vegetated areas, it can be difficult to accurately position electrodes. Moreover monitoring unstable ground from landsliding, electrode positions can shift resulting in

![Fig. 10. Comparison of dipole–dipole and optimized array images of a landslide. Both images show the geological structure of the landslide, but in the optimized image the lower sandstone/mudstone interface is better resolved.](Image) British Geological Survey (c) NERC 2013.
systematic data error which cannot be reduced through reciprocal error filtering (Oldenborger et al., 2005; Wilkinson et al., 2008, 2010a; Zhou and Dahlin, 2003). Approaches to reduce the impact of these effects include the selection of measurement array geometries that are less sensitive to positional errors (Wilkinson et al., 2008), and in the case of moving electrodes, to estimate electrode position using a position inversion routine (Wilkinson et al., 2010a).

6.4. Survey design

For very long 2-D survey lines, and for 3-D imaging grids, it can be impractical to undertake measurements in a single deployment due to the long cable lengths required. Consequently, very long 2D lines are often surveyed using overlapping sections (e.g. Donohue et al., 2012), and 3-D surface surveys are often undertaken using a network of lines, where a single line is incrementally migrated across the surface to build up a measurement set comprising data from multiple lines (e.g. Bentley and Gharibi, 2004; Dahlin et al., 2002; Rucker et al., 2009a). Where a single line orientation is used, linear features parallel to the line direction can be poorly resolved (Chambers et al., 2002), and banding or herring-bone effects can be present in the model (Loke and Dahlin, 2010). Mitigation measures include: roll-along (or multiple line) data acquisition methodologies (Dahlin et al., 2002); orthogonal line directions (Chambers et al., 2002; Gharibi and Bentley, 2005); line separations of no more than two electrode spacings (Chambers et al., 2002; Gharibi and Bentley, 2005); and appropriate inversion settings (e.g. horizontal diagonal roughness filters) (Farquharson, 2008; Loke and Dahlin, 2010).

6.5. Smoothing

Smoothness constrained inversion, which dominates the field of geoelectrical imaging, typically produces smoothly varying resistivity distributions, and so the precise location of geological or engineering interfaces can sometimes be difficult to determine in the absence of a priori subsurface information. In addition to robust (L1-norm) inversion (Loke et al., 2003), a range of other interface detection approaches have been applied. These include image analysis using gradient-based edge detectors (Chambers et al., 2012; Elwaisef and Slater, 2010; Hsu et al., 2010), and alternative inversion approaches, such as laterally constrained inversion (Wisen et al., 2005), inclusion of sharp boundaries (Chen et al., 2012; Smith et al., 1999) or joint inversion with other geophysical data (Bouchetta et al., 2012). In addition, high-contrast heterogeneities in the subsurface that are small compared to the model cell-size cannot be accurately modeled, and so can hinder convergence between measured data and the resistivity model during the inversion process. However reducing the model cell size increases the computer memory and time required for the data inversion, as well as possibly requiring a higher damping constraint to stabilize the inversion model (Loke and Dahlin, 2010; Loke and Lane, 2004). From numerical tests with 2-D models, Sasaki (1992) and Loke (2012) showed that using a model cell size of half the unit electrode spacing seems to provide the optimum balance.

6.6. Three-dimensional structures

Off-line three-dimensional structures (including topography) cannot be accurately modeled by 2-D inversion, and so can distort resistivity models (Bentley and Gharibi, 2004; Chambers et al., 2002; Nimmer et al., 2008). These effects can be reduced by ensuring lines are oriented perpendicular to the strike of elongated structures and by using a 3-D survey approach in complex settings. Although it should be noted that the edges of 3-D models will also be influenced by 3-D structures outside of the survey area.

6.7. Calibration and interpretation

ERT provides only indirect information of subsurface physical properties such as lithology, moisture content, or temperature, which are of principal interest to geologists, engineers and hydrologists. Due to the overlapping resistivity ranges of many common earth materials, and the influence of varying salinity, moisture and temperature, robust interpretation of resistivity images requires other sources of ground truth data. For ground investigation, resistivity imaging is routinely used alongside intrusive methods such as drilling and cone penetration testing (CPT) (Wisen et al., 2005). In-situ measurement of resistivity (e.g. CPT resistivity profiles) or laboratory testing of subsurface materials (e.g. Jackson et al., 2006; Russell and Barker, 2010) can be used to directly constrain the inversion of resistivity data by fixing the resistivities of known regions of the model (e.g. Günther and Rücker, 2009; Pidlisecky et al., 2006). For in-situ or laboratory measurements of resistivity to be suitable for constraining inversion, they must provide information at a scale appropriate to the resolution of the ERT model. This is particularly crucial in highly heterogeneous subsurface conditions. In the case of CPT derived resistivity measurements, along-profile variability can be used to determine spatial averaging requirements. Likewise, for laboratory measurements of resistivity, sample volumes and distributions representative of the ERT survey resolution and material heterogeneity are required. Investigation of the relationships between resistivity and temperature (Hayley et al., 2007, 2010; Musgrave and Binley, 2011), pore fluid salinity (Hayley et al., 2009; Lemkine et al., 2012; Monego et al., 2010), moisture content (Brunet et al., 2010; Cuisiani et al., 2006), and lithology (e.g. Russell and Barker, 2010; Shevlin et al., 2007) are increasingly being undertaken to aid the interpretation of ERT sections and time-lapse resistivity monitoring data.

6.8. Anisotropy

The influence of even moderately anisotropic media on the results of resistivity inversion that assumes isotropic conditions can produce significant distortions in electrical tomograms (e.g. Greenhalgh et al., 2010; Herwanger et al., 2004). Typical geological causes of anisotropy include fracturing, jointing, layering and rock fabric (e.g. strong alignment of grains slates and shales). Detection of anisotropy has typically been undertaken using azimuthal (Busby, 2000) and square array (Matias, 2008) techniques. However, the most effective approach is perhaps surface to borehole imaging arrays, which unlike surface arrays, are sensitive to anisotropy associated with vertical or sub-vertical axes of symmetry, such as horizontal layering (Greenhalgh et al., 2010). To address the problem of anisotropy, anisotropic resistivity inversion schemes have been developed (Greenhalgh et al., 2009; Herwanger et al., 2004; Kim et al., 2006; Pain et al., 2003); however, these are limited by number of factors, including the requirement to solve for additional parameters that exacerbates the problem of non-uniqueness, and the need for subsurface electrodes to effectively detect anisotropy associated with horizontal layering (Greenhalgh et al., 2010).

7. Conclusions and future trends

There has been tremendous progress in the geoelectrical method over the last 25 years. The images of the subsurface the method provides have become more geologically realistic, from simple 1-D layered models to complex 3-D structures varying with time. There have been parallel developments in field instrumentation, data inversion techniques, and automatic interpretation software that have made this possible. It is now an established technique widely used in mineral exploration, environmental, engineering, and hydrological surveys not only on land but also in aquatic regions as well. In the near future, we foresee an increasingly wider use of 3-D surveys in complex areas in place of 2-D surveys, particularly with the wider availability of multi-channel instruments. New research in practical
implementation of L.P. measuring electrodes and cables with the less powerful systems commonly used in engineering and environmental surveys (Dahlin and Leroux, 2012) will provide useful additional information without increasing the survey time and cost. Measurement of resistivity variations in both space and time with automatic monitoring systems will become increasingly important in detecting incipient problems such as seepage from dams, landslides and gas accumulation in landfills; as well as in assisting the optimal extraction of resources. To fully exploit the data from multi-dimensional geological surveys, an understanding of the limitations of the technique and the proper use of regularization constraints is important. The greatest limitation of the electrical method is the rapid reduction of resolution with distance from the electrodes. This limitation can be partly reduced by the use of subsurface electrodes located nearer to the region of interest, and the use of other geophysical and geotechnical data (if available) to constrain the inversion model.

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