Recent Advances in the Geoelectrical Method and New Challenges: A Software Perspective

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Summary

The electrical method is one of the oldest geophysical exploration methods dating back to the 1910's. It has been used in diverse fields ranging from archaeological, environmental, hydrological, geotechnical and mineral exploration surveys. Many of the developments that have made it possible for resistivity surveys to be used for such complex environments took place within the last 30 years. It has transformed from a 1-D tool from the 1910s until the 1980s, to a 2-D surveys in the 1990s, to 3-D surveys in the 2000s and to present day 4-D surveys. The widespread use of multi-dimensional geoelectrical surveys was made possible by the development of multi-electrode instruments designed for dense data coverage accompanied by fast inversion software for PCs to carry out the numerically intensive calculations. This has made it possible for small geophysical companies to carry out 2-D and 3-D geoelectrical surveys in areas with complex geology. Selected on-going research areas including electrode array optimization techniques, time-lapse surveys with electrodes displacements, vector array surveys and data inversion, and inversion of very large data sets from surveys with mobile systems are briefly discussed.

Introduction

The geoelectrical survey method dates back to the work of the Schlumberger brothers in the 1910's. Over the last century it has been used in many fields including environmental, engineering,

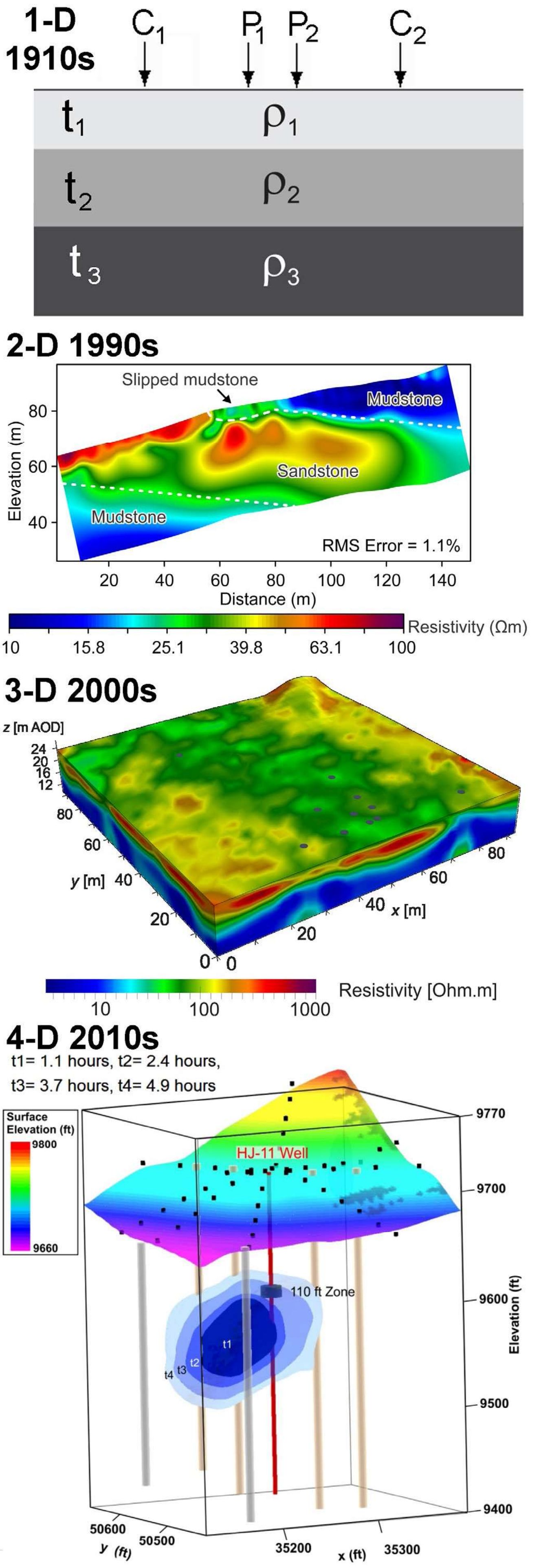

Figure 1. Progress in the geoelectrical method over the last century (Loke et al., 2013).

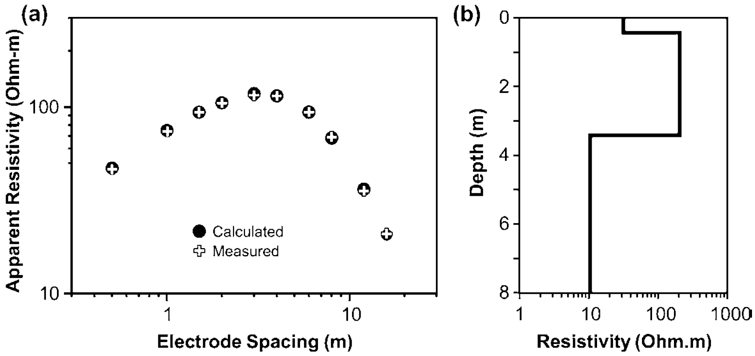

Figure 2. Example of resistivity sounding curve and 1-D model.

hydrological, archeological and mineral exploration studies (Loke et al., 2013). It has become one of the standard tools used by many geophysical companies, particularly for near-surface surveys. Figure 1 illustrates the progress in geoelectrical surveys over the last century. There has been a steady march towards the creation of more realistic earth models that more closely match the true geology. It has progressed from simple 1-D layered earth models to 4-D models that show the changes in the subsurface resistivity with space and time. This has been driven by advances in instrumentation, field survey techniques, mathematical inversion theory, PC (personal computer) technology and software. One reason for the popularity of the resistivity method is the relative simplicity and low cost of the field instruments. A resistivity measurement basically requires an electrical current source that injects a current into the ground through two metal electrodes (C1 and C2 in Figure 1) and measuring the potential difference at another two electrodes (P1 and P2 in Figure 1). By making the measurements with different arrangements of the electrodes at various points on the ground surface, the true resistivity of the subsurface can be reconstructed using an inversion algorithm (Menke, 1989). As the resistivity method is used by many small geophysical companies, robust software that can run at a reasonable pace on inexpensive PCs has played a vital role in bringing this technique to the masses.

The 1-D era: 1910s to 1980s

The resistivity method was initially mainly used as profiling or sounding surveys (Keller and Frischknecht, 1966). In a profiling survey, the spacings and arrangements of the electrodes are kept fixed and the whole array is moved along the survey line. In a sounding survey, the center point of the array is kept fixed while the distances between the electrodes are progressively increased to get deeper information. Quantitative interpretation is only practical for the sounding survey where a 1-D layered earth model is used (Figure 1). The 'ridge regression' or damped least-squares method (Inman, 1975) is widely used for 1-D data inversion. One important mathematical development was the linear filter method in the 1970s that provides a fast method to calculate the apparent resistivity values for the 1-D model (Koefoed, 1979). This made it possible to automatically carry out the inversion of the sounding survey data using the early PCs that appeared at the beginning of 1980s. Figure 2 shows a typical sounding curve and computer model. The main limitation of the 1-D sounding method is that it assumes the subsurface resistivity only changes with depth and does not change in the horizontal direction. In most areas there are significant lateral variations and the 1-D model is not geologically realistic. However, sounding surveys are still used, particularly for deep groundwater mapping in less developed countries where the more expensive multi-electrode computerized resistivity meters are not readily available.

The 2-D era: 1990s

Since the 1960s, attempts were made to overcome the limitations of 1-D surveys by making 2-D measurements, particularly in the mining industry using the dipole-dipole array together with I.P. measurements. Measurements are made using different electrode spacings as well as at different positions along a line to measure both the vertical and lateral changes in the subsurface resistivity. The data is usually plotted in the form of a pseudosection (Edwards, 1977). Initially the data interpretation was largely qualitative. Mathematical techniques to solve the 2-D forward modelling (Dey and Morrison, 1979) and inversion (Smith and Vozoff, 1984) problems were developed but they were largely confined to academic studies using mainframe computers. A major advance was made in the early 1980s with the development of multi-electrode systems (Griffiths and Turnbull, 1985) where 25 or more electrodes are attached to a multicore cable, and a microprocessor within the resistivity meter automatically selects the different sets of electrodes to scan the subsurface. This provided a fast and efficient method to collect the 2-D data. However, interpretation of the data was relatively crude. Attempts were made to gleam the subsurface structures using the contour shapes in the pseudosection or a slow manual refinement of a 2-D forward model. The pseudosection contour shapes can differ greatly from true structure as it also depends on the electrode array used (Figure 3a). The manual refinement method took days (Griffiths and Barker, 1993) with the available software and PCs, and required some technical expertise that involves visually comparing the measured and calculated apparent resistivity pseudosections and modifying the forward model manually. A turning point was in the mid-1990s with the availability of 2-D inversion software that automatically converts the pseudosection data into a model in minutes using inexpensive PCs (Loke, 1994; Loke and Barker, 1996). There were also significant developments in regularized inversion algorithms that ensures the model resistivity changes spatially in a smooth manner (deGroot-Hedlin and Constable, 1990; Oldenburg and Li, 1994). Multi-electrode systems are now available from many companies with prices ranging from USD12,000 to USD100,000 depending on the features offered. This enabled more complex geology to be mapped rapidly and accurately on a routine basis by small geophysical companies. This illustrates that both robust (and inexpensive) hardware and software are needed for a geophysical method to be widely used. The EEGS played an early role in the spread of the 2-D

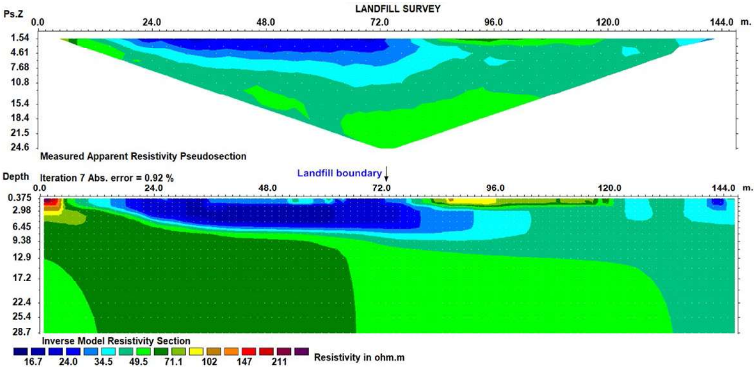

Figure 3. Example of 2-D resistivity survey pseudosection and inverse model (Niederleithinger, 1994).

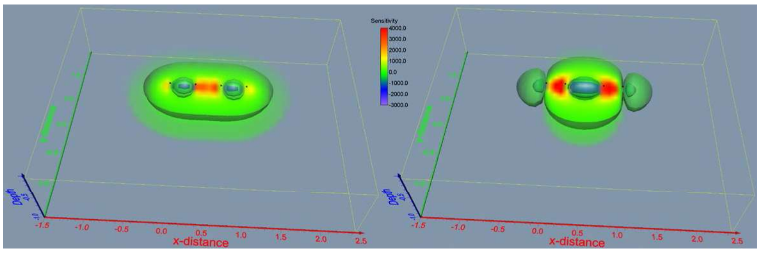

Figure 4. 3-D sensitivity plots for the Wenner and dipole-dipole arrays.

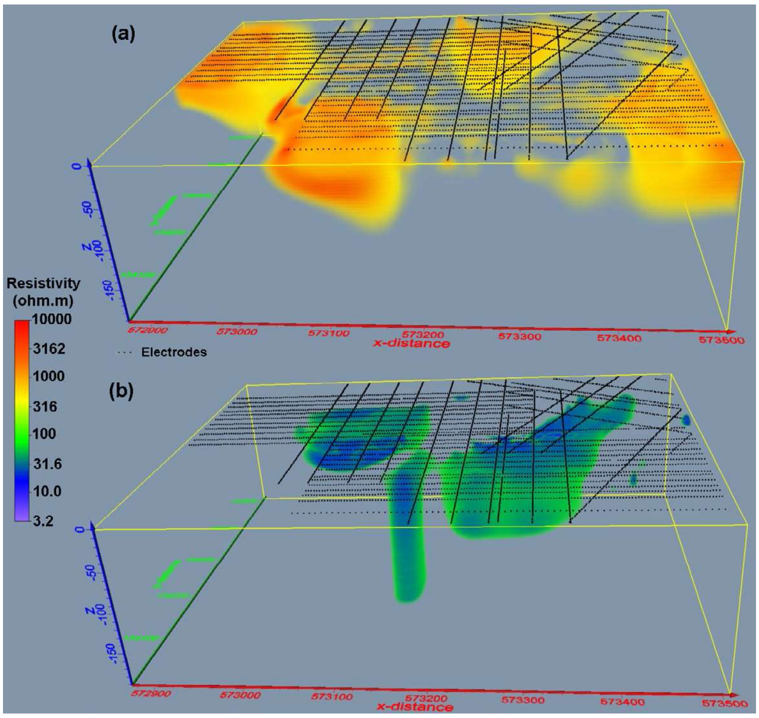

Figure 5. 3-D model plots for the Hanford waste disposal site (Rucker et al., 2009) showing (a) high resistivity zones above 400 ohm.m and (b) low resistivity zones below 80 ohm.m.

resistivity method. The data set in Figure 3 was first presented at a SAGEEP conference (Niederleithinger, 1994). The 2-D ERT (Electrical Resistivity Tomography) method has enjoyed great success, particularly in areas with elongated geological structures where the 2-D approximation is reasonably accurate. However, in very complex areas, the 2-D model might suffer from artifacts due to structures located to the sides of the survey line. The severity of the 3-D effects depends on the array type. The high sensitivity zone of the Wenner array is elongated along the line of electrodes (Figure 4), thus it is less sensitive to 3-D effects. The high sensitivity zone for the dipole-dipole array is elongated perpendicular to the array axis that makes it is more sensitive to 3-D effects. However, 2-D surveys are probably the most commonly used ERT method due to the comparatively low cost and it gives a sufficiently accurate model in many areas.

The 3-D era: 2000s

In very complex environments, a 3-D approach is needed to accurately resolve the structures of interest. Mineral deposits, such as base and precious metals, are commonly found in geologically complex areas. The high value of the minerals justified the higher costs of 3-D resistivity and I.P. surveys in order to more accurately map the deposits. New field techniques, such as the offset pole-dipole array (White et al., 2001), were designed in order to survey large areas rapidly. Many landfill and water disposal sites also have very complex structures and thus were among the early users of 3-D surveys (Dahlin et al., 2002). The availability of more powerful PCs and efficient multi-channel resistivity meter systems made 3-D surveys a practical tool. While ideally the electrodes should be arranged in a rectangular grid for maximum data coverage (Li and Oldenburg, 1992), many 3-D data sets are collated from independent 2-D lines. Modern multi-core PCs have greatly extended the range of data sets that can be processed with greater resolution. Figure 5 shows the inverse model from the Hanford waste disposal site (Rucker et al., 2009). This is a fairly large data set with over 5400 electrode positions, 86000 data points and 700000 model cells. The inversion took 59 hours on a PC with an 18-core CPU and 256GB RAM. There are linear near-surface high resistivity features related to concrete cribs (Figure 5a). The low resistivity plot (Figure 5b) show an intriguing narrow vertical structure, and two large plumes which are probably leakages from the waste storage units. 2-D and 3-D surveys have also been carried out in aquatic areas covered by a water layer. Some surveys use electrodes planted on the river or sea bed similar to a land survey (Acworth and Dasey, 2003; Dahlin and Loke, 2018). Surveys have also been carried out using a streamer towed behind a boat (Rucker and Noonan, 2013; Oikonomou et al., 2019).

The 4-D era: 2010s

In a time-lapse survey, the measurements are repeated using the same grid of electrodes to detect temporal changes in the subsurface. Time-lapse surveys have been used to monitor dams, levees, landslides, landfills, aquifers and solvent extraction of minerals (Sjödahl et al., 2008; Poje et al., 2018). Sophisticated automatic systems that make the measurements at regular intervals using a permanently installed grid of electrodes with telemetric control and data transfer now available (Uhlemann et al., 2017). New inversion techniques that applies a smoothness-constraint across the time models to reduce temporal artifacts have been developed (Kim et al., 2009). Figure 6 shows an example from a landfill monitoring site at Filborna, Sweden (Loke et al., 2014)

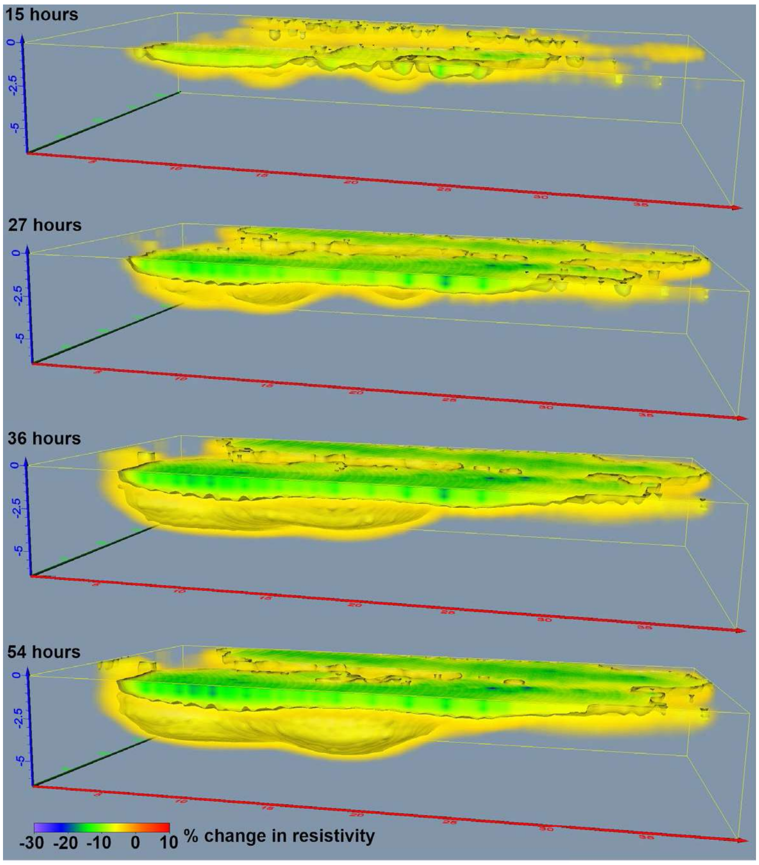

Figure 6. Migration of rainwater down a permeable zone at the Filborna landfill monitoring site (Loke et al., 2014). The times after the start of the downpour are shown. The water table is at 5 meters depth.

where measurements were made every 3 hours from 2008 to 2011. The main purpose was to monitor methane gas migration from the landfill but a heavy rainfall downpour lasting about 20 hours provided an example data set for mapping migration of rainwater downwards through the landfill. The migration of the rainwater down a permeable zone within the landfill is approximately shown by the boundary with a 4% decrease in the resistivity (Figure 6).

New Challenges

In this section, we briefly touch on few selected areas of ongoing research.

Array optimization - Most surveys use conventional arrays such as the Wenner, Wenner-Schlumberger, dipole-dipole, pole-dipole and multiple-gradient (Loke et al., 2013). There has been considerable research in methods to find the optimum set of arrays based on some objective criteria such as the model resolution (Wilkinson et al., 2012; Uhlemann et al., 2018). While it has been shown that choosing the proper set of arrays can significantly improve the resolution of the subsurface, these techniques have not yet reached the stage where they can be routinely used by non-experts in field surveys.

Electrodes displacements in 4-D surveys - In time-lapse surveys, it is normally assumed the electrodes are fixed with known positions and only the subsurface resistivity changes with time. A special problem arises in landslide monitoring where the electrodes might have moved between the times the measurements were made. The changes in the positions of the electrodes, as well as the changes in subsurface resistivity, have to be estimated from the resistivity data. There has been considerable progress in this field and the state of the art has almost reached the stage where it can be used routinely (Wilkinson et al., 2016; Loke et al., 2018).

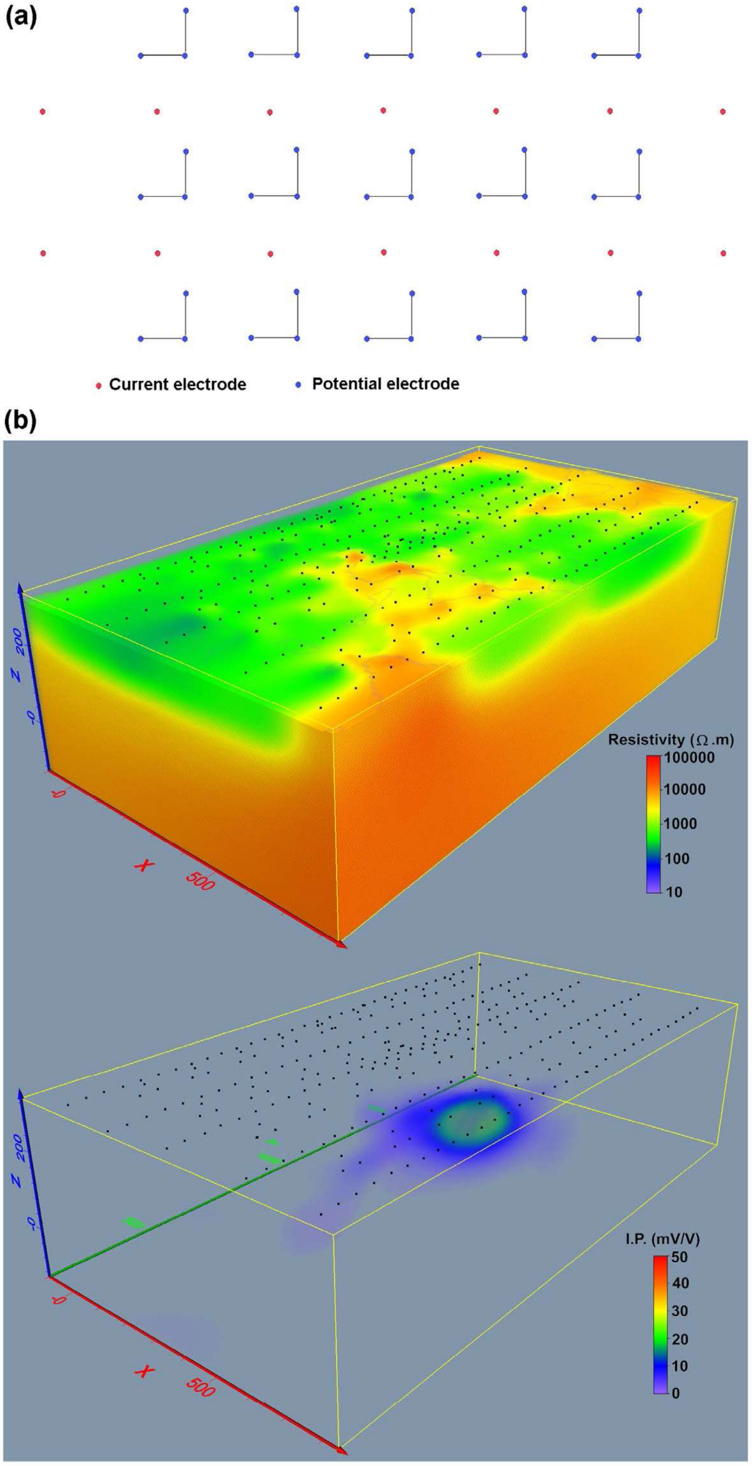

Figure 7. (a) Schematic diagram of vector array survey layout. (b) Resistivity and I.P. models from a field survey using the Iris Instruments FullWaver system (Loke et al., 2019).

Vector arrays – One problem in the use of the offset pole-dipole and dipole-dipole array occurs when the orientation of a potential dipole with respect to the current dipole is such that it almost lies on an equipotential line. The measured potential signal can be very small and sensitive to noise. In a vector array survey, two potential dipoles that are at right angles

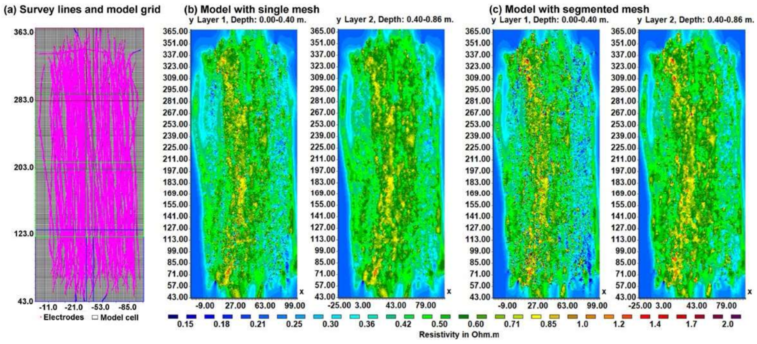

Figure 8. (a) Survey lines and model grid from an underwater survey in Greece (Oikonomou et al., 2019). The sections used in the segmentation method are shown by the colored lines. Top two layers of the inverse model using (b) standard monolithic and (b) segmented mesh inversions.

with each other are used at each potential station (Figure 7a). Theoretically the combined signal strength is independent of the orientation of the two potential dipoles with respect to the current dipole. This arrangement was originally proposed by Zonge (1994) for reconnaissance surveys but more recently it has been used for detailed surveys (Truffert et al., 2019). Preliminary results from the surveys and data inversion appear promising (Loke et al., 2019). Figure 7b shows the resistivity and I.P. models from a survey using the Iris Instruments FullWaver system. A single compact I.P. anomaly with values of over 40 mV/V and average diameter of about 150 m is detected at about 30 to 160 m below the surface in the right side of the survey area. There are higher resistivity values in the upper 200 meters near the I.P. anomaly that could be related to the mineralization.

Segmentation of large 3-D data sets – While new PCs come with greater processing power and memory, it very often leads to new surveys with even larger data sets that stretches the computational resources. Surveys with mobile systems can lead to very huge data sets. These systems have a limited number of takeouts on a cable that is moved during the survey for lateral coverage. A capacitively coupled system (Kuras et al., 2007) is commonly used for land surveys, while a streamer towed behind a boat has been used for aquatic surveys (Rucker and Noonan, 2013). One feature of the mobile systems is the limited footprint of an electrode array that is set by the length of the cable. Figure 8a shows the layout from an archaeological survey in Greece using a mobile streamer dragged along the sea bottom below about 1 m of water. The dipole-dipole array with a dipole length of 1 m and 'n' values ranging from 1 to 10 was used. There are 215875 electrode positions and 165610 data points in this data set. The model grid used in the data inversion is 129 by 325 m with cell widths of 1 m in both the x and y directions and 9 layers giving a total of 373,248 model cells. Figure 8b shows the top 2 layers (where the cultural structures of interest are located) of the inverse model obtained using a single finite-element mesh with more than 9 million nodes. The inversion took 13.5 days using a PC with an 18-core CPU. In the survey, the maximum distance between two electrodes used in a measurement was 12 meters which is much smaller than the model grid size of 129 by 325 meters. The finite-element mesh was subdivided into 8 segments (Figure 8a) with some overlap to minimize discontinuities in the calculated apparent resistivity values near the boundaries. The inversion took about 1.9 days, or about 7 times faster than using a single large mesh. There are no significant differences in the models using a single mesh (Figure 8b) and a segmented mesh (Figure 8c).

Conclusions

There has been rapid progress in the geoelectrical method, from 1-D to 4-D surveys, over the last 30 years that has transformed the industry. This has been made possible by advances in field instruments that made the collection of large data sets possible, and corresponding software developments that enabled the efficient processing of the data with inexpensive PCs. This has enabled small geophysical companies to carry out 2-D and 3-D surveys at a reasonable cost. Traditional 1-D sounding surveys have been largely replaced by 2-D surveys that give more realistic models of the subsurface. A 3-D survey and model is needed in areas with complex geology. Over the past decade there have been many developments in automatic monitoring systems and software for 4-D surveys to map temporal changes in the subsurface.

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