4 Electrical resistivity method

In this chapter the electrical resistivity method, a mainstay of near-surface applied geophysics for many decades (Keller and Frischknecht, 1966; Bhattacharya and Patra, 1968) is described. The technique has enjoyed a resurgence in popularity since the mid 1990s (Loke, 2000; Dahlin, 2001; Zonge *et al*., 2005) due to rapid and impressive advancements in data acquisition, forward modeling, and inversion capabilities.

The fundamental steps involved in the resistivity method may be outlined as follows. An electric current I [amperes, A] is directly injected into the ground through a pair of electrodes and the resulting voltage V [volts, V] is measured between a second pair of electrodes. The impedance $Z = V/I$ [V/A] of the Earth is formed; it is the ratio of the voltage output V measured at the potential electrodes to the current input I at the current electrodes. The impedance is then transformed into an apparent resistivity ρ_a [ohm-meters, Ωm] which is an intuitively understood indicator of the actual underlying electrical resistivity structure $\rho(\mathbf{r})$ of the Earth, where **r** is the position vector. Different arrangements of the electrodes permit the apparent resistivity to be determined at different depths and lateral positions. A map of the apparent resistivity plotted at these locations is termed a *pseudosection* (Loke, 2000). The pseudosection is then inverted to obtain a two- or three-dimensional (2-D or 3-D) resistivity section $\rho(\mathbf{r})$ of the ground. Finally, a geological interpretation of the resistivity section is performed that incorporates, as far as possible, any prior knowledge based on outcrops, supporting geophysical or borehole data, and any information gained from laboratory studies of the electrical resistivity of geological materials (see Table 4.1).

Table 4.1 Resistivity of common geological materials

Geomaterial	Resistivity [Ωm]
Clay	1–20
Sand, wet to moist	20–200
Shale	1–500
Porous limestone	$100–10^3$
Dense limestone	$10^3–10^6$
Metamorphic rocks	$50–10^6$
Igneous rocks	$10^2–10^6$

4.1 Introduction

The electrical resistivity method has a long history in applied geophysics, including the pioneering work in 1912 by Conrad Schlumberger of France. A few years earlier than that, Swedish explorationists had experimented with locating conductive bodies by moving around a first pair of potential electrodes while keeping a second pair of current electrodes in a fixed location (Dahlin, 2001).

The two case histories described below introduce the reader to examples of recent usage of the resistivity method. The first example is a study of a hydrogeological problem at a human-impacted site of historical significance. The second example relates to the use of resistivity data for imaging liquid hazardous waste at a nuclear-waste site in the USA.

Example. Investigation of an historic WWII site.

The D-Day invasion site at Pointe du Hoc, France (Figure 4.1a) is an important WWII battlefield and remains today a valuable cultural resource but its existence is jeopardized by the risk of potentially devastating cliff collapses. The resistivity method was used there to study the effect of groundwater infiltration on the cliff stability. The great amount of buried steel, concrete, and void spaces at the site renders hydrogeological interpretation of the resistivity data challenging.

A resistivity profile was acquired by laying out a line of electrodes passing within a few meters of a 155-mm gun casemate (Figure 4.1b). The resistivity section shown in

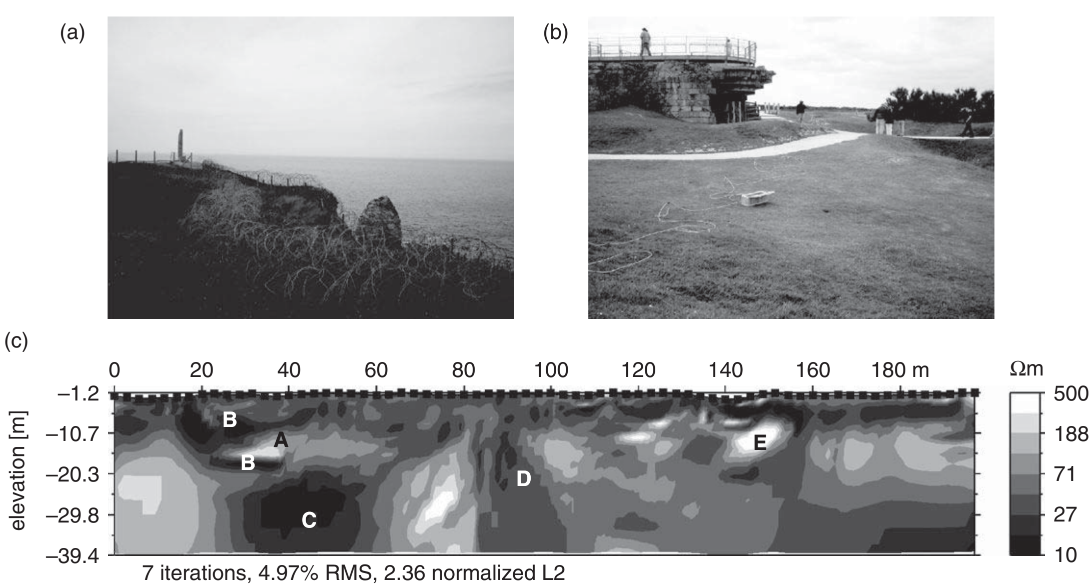

Figure 4.1 (a) WWII battlefield, Pointe du Hoc, France. (b) Resistivity data acquisition passing close to an historic German fortification. (c) Resistivity section showing natural and cultural subsurface features. Labels A–E described in the text. After Everett *et al*. (2006).

Figure 4.1c was constructed and interpreted by Everett *et al*. (2006), as follows. The small zone of high resistivity (A) showing at ~ 15 m depth, with the low-resistivity halo (B) surrounding it, is the geophysical signature of the casemate and its foundations. The larger, deeper low-resistivity zone (C) extending from 25 to 60 m along the profile is likely of geological origin, perhaps a zone of groundwater accumulation. The vertical zone of high conductivity (D) at ~ 90 m is not immediately associated with any known cultural features; it is interpreted as a vertical conduit for groundwater that flows from substantial depths to the surface. The highly resistive zone (E) at distance 145–150 m along the profile is explained by a large slab of buried concrete.

Example. Investigation of the Hanford nuclear site.

Discharge of millions of liters of hazardous liquid electrolytes since the 1940s has occurred at the Hanford nuclear facility in eastern Washington State, USA. Subsurface resistivity imaging of the resulting contaminant plumes in the vadose zone beneath the site remains a challenging task due to the presence of storage tanks, pipelines, metal fences, and other cultural infrastructure. To directly access the deep vadose region beneath the near-surface zone of cultural noise, Rucker *et al*. (2010) took advantage of the large number of existing steel-cased monitoring wells at the site. They utilized the steel casings as long cylindrical electrodes in a novel well-to-well (WTW) pole–pole configuration.

A total of 110 steel casings from wells with lengths up to 90 m were used as electrodes in the WTW survey. The resulting voltage measurements were of reasonable quality, with only ~ 10% of the ~ 12 000 readings being rejected due to high repeat errors. The result of a 3-D inversion of data from 87 centrally located wells is shown in Figure 4.2. Two major low-resistivity anomalies can be identified in this plan-view map at depth 1.4 m. The first, in the lower-left region of the survey, corresponds to the area of a historical non-point source dispersal of nitrate-contaminated (1–2 mol/L) wastewater. The second low-resistivity anomaly occurs in the vicinity of leaking storage tanks T-103 and T-106. The tanks are documented to have discharged into the vadose zone a volume of liquid contaminant exceeding 440 kL.

4.2 Fundamentals

The resistivity technique is founded on basic principles familiar to all scientists and engineers working in the physical sciences. Consider a cylindrical sample of material of length L [m], resistance R [Ω] and cross-sectional area A [m^2]. The resistivity ρ [Ωm] is a material property equal to $\rho = RA/L$, see Figure 4.3. The spatially variable resistivity

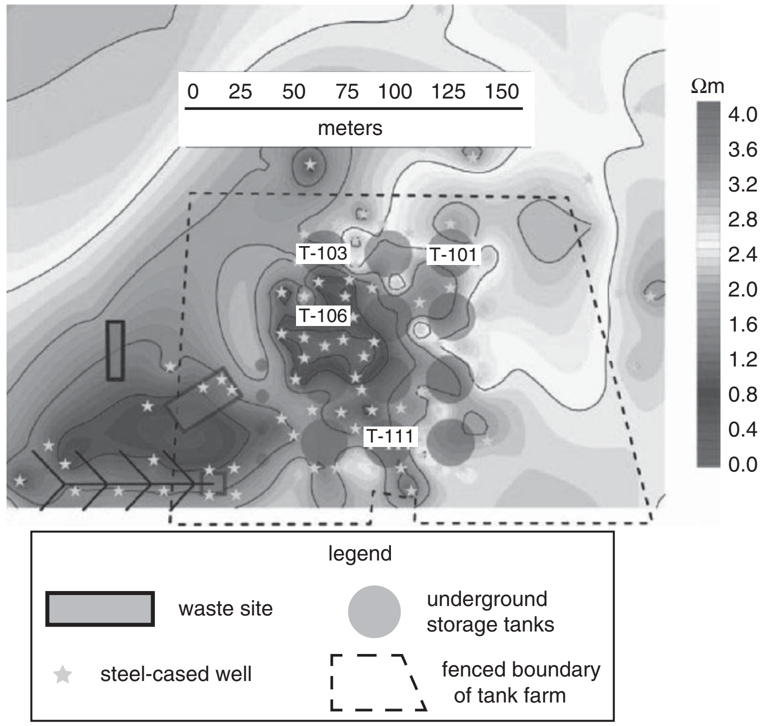

Figure 4.2 WTW resistivity inversion at the Hanford nuclear facility; depth slice at 1.4 m. After *Rucker et al*. (2010).

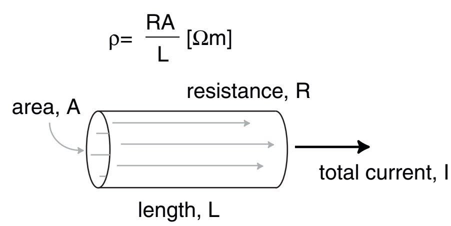

Figure 4.3 Definition of resistivity ρ.

$\rho(\mathbf{r})$ of the subsurface is the physical property that is sensed by the resistivity method. The reciprocal of the resistivity is the electrical conductivity $\sigma = 1/\rho$, which by convention is the preferred quantity used in the electromagnetic and ground-penetrating radar geophysical techniques (see Chapters 8 and 9). Electrical conductivity is a measure of the ability of a material to sustain long-term electric current flow. Thus, electric current can flow readily in low-resistivity zones and is weak or absent in high-resistivity zones.

A general scenario is shown in Figure 4.4, in which a battery is connected to two electrodes which serve as a current source/sink pair. The electric current streamlines (line segments) and equipotentials (colors) are displayed in the figure for a current injection of $I = 1$ A and uniform resistivity $\rho = 1$ Ωm.

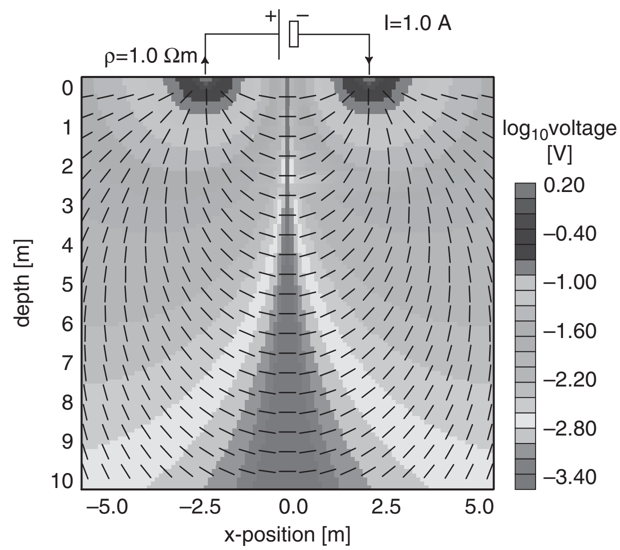

Figure 4.4 Potential and streamlines of electric current for a point source and a point sink of current.

To understand how the resistivity method is used to estimate Earth resistivity, first recognize that the subsurface current density **J** is related to the electric field **E** by Ohm's law $\mathbf{J} = \sigma \mathbf{E}$ so that

$$\mathbf{E} = \frac{\mathbf{J}}{\sigma} = \rho \mathbf{J} = \frac{I\rho\, \hat{\mathbf{r}}}{4\pi r^2}. \tag{4.1}$$

Ohm's law, stated in Equation (4.1), is nothing more than the generalization to continuous media of the familiar law as it applies to a simple resistive circuit, $V = IR$, where V is voltage, I is current, and R is resistance.

Next, consider an electric current I injected, at the origin of a spherical coordinate system, into a hypothetical whole-space of uniform resistivity ρ. Suppose the return electrode is placed at infinity. The situation is depicted in Figure 4.5. In the vicinity of the injection point, the current will spread out symmetrically in all three dimensions. At point P at distance r from the injection point, using Equation (4.1) the current density **J** is

$$\mathbf{J} = \frac{I\, \hat{\mathbf{r}}}{4\pi r^2}, \tag{4.2}$$

where $4\pi r^2$ is the area of a spherical surface of radius r. The numerator of Equation (4.2) expresses the magnitude and direction of the current at point P while the denominator expresses the cross-sectional area through which the current uniformly flows.

What is the voltage V measured at observation point P in Figure 4.5? Voltage is *defined* as the work done by the electric field **E** in moving a test charge from infinity to point P. Work is defined by the product of work and distance, or in our case the line integral

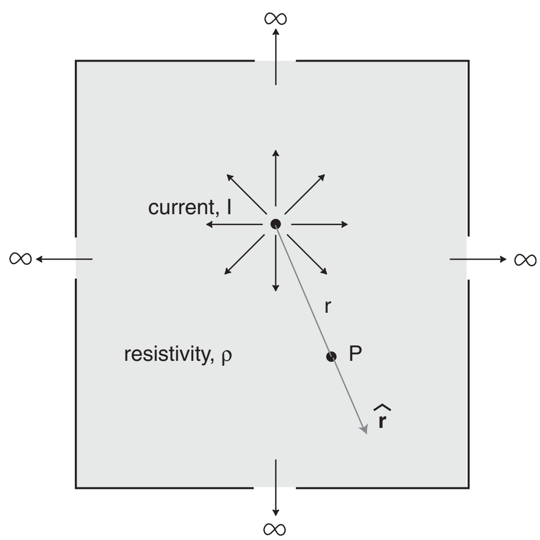

Figure 4.5 Current injection into a wholespace of uniform resistivity ρ.

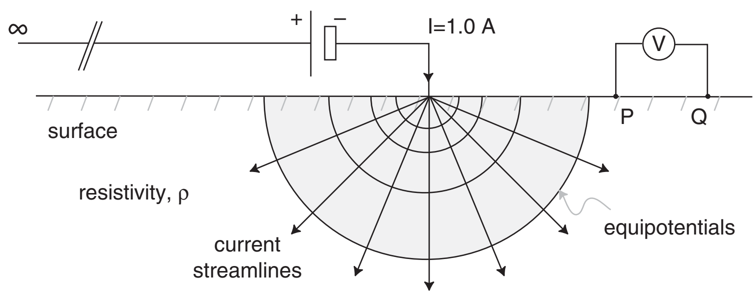

Figure 4.6 Voltage measured between points P and Q for a point source of electric current injected into a halfspace of uniform resistivity ρ.

$$V = \int_C \mathbf{E} \cdot d\mathbf{s}, \tag{4.3}$$

where C is any path from infinity terminating at point P. Hence the voltage at P is

$$V = \int_r^\infty \mathbf{E} \cdot d\mathbf{r} = \int_r^\infty \frac{I\rho}{4\pi r^2} dr = \frac{I\rho}{4\pi r}. \tag{4.4}$$

Now suppose that the injection point is located on the surface of a halfspace representing the Earth, as shown in Figure 4.6.

The electric current, which cannot flow through the non-conducting air, flows radially outward through a *hemisphere* of radius r and surface area $2\pi r^2$. Hence, the current density