Surface and borehole electrical resistivity tomography

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Introduction

Surface electrical resistivity surveying is based on the principle that the distribution of electrical potential in the ground in the vicinity of an electrode array depends on the electrical resistivity distribution of the surrounding soils and rocks. The usual practice in the field is to inject a direct or slowly alternating electrical current through two electrodes implanted in the ground and to measure the difference in potential between two other electrodes. The current is either direct, commutated direct (i.e. an alternating square-wave) or low frequency (typically below 20 Hz) alternating.

Applications

In civil engineering applications, resistivity surveys can be useful for detecting bodies of anomalous materials or for estimating the depths of bedrock surfaces. In coarse granular soils, the groundwater surface is generally marked by an abrupt change in water saturation and thus by a change of resistivity. Therefore, this technique is very useful in hydrogeophysics. Resistivity surveys are also commonly carried out to explore abadonned man-made structures such as waste sites or archeological remains.

Electrical properties of rocks and units

The electrical resistivity (or simply resistivity) of all materials governs the relationship between the current density and the gradient of the electrical potential. Variations in the resistivity of subsurface materials, either vertically or laterally, produce variations in the relationships between the applied current and the potential distribution as measured on the surface, and thereby provides information on the composition, extent and physical properties of the subsurface materials. The various electrical geophysical techniques only distinguish geological units when a contrast exists in their electrical properties. No resistivity contrast means no resistivity anomaly!

Resistivity (ρ) has the dimension of ohm-meter (Ωm). The conductivity (σ) of a material is defined as the reciprocal of its resistivity and is expressed in Siemens per meters (S/m). Resistivity is an intrinsic property of a material, in the same sense that density and elastic moduli are intrinsic properties. These properties do not depend on the shapes of the material samples.
In most earth materials, the conduction of electric current takes place almost entirely in the water occupying the pore spaces or joint openings, because most soil- and rock-forming minerals are essentially non-conductive (noticeable exceptions are ore bodies for example). Since the conduction of current in soil and rock is through the electrolyte (i.e. the ions in the water carry the current) contained in the pores, resistivity is governed largely by the porosity of the material and the geometry of the pores. Pore space may be in the form of intergranular voids, joint or fracture openings, and closed pores, such as bubbles or vugs (in lavas). Only the interconnected pores (effective porosity) contribute to electrical conductivity; the geometry of the interconnections, or the tortuosity of current pathways, also influences conductivity.

The resistivity of saturated porous material can be linked to the resistivity of the pore water via the formation factor used in different empirical laws (e.g. Archie's Law). The formation factor is a function only of the properties of the porous medium, primarily the porosity and pore geometry. Saturation is another parameter that influences the resistivity of a rock. Moreover, since water forms a conductive electrolyte when chemical salts are in solution, conductivity is proportional salinity. Finally, increasing temperature increases the conductivity of the electrolyte because the viscosity of the fluid decreases. There is no simple link between resistivity and permeability.

Fine-grained clay or shale generally has lower resistivities than soils or rocks composed of bulky mineral grains. Although clay particles themselves are non-conductive when dry, the conductivity of pore water in clays is increased by the desorption of exchangeable cations from the clay particle surfaces. Clays and a few other minerals, notably magnetite, carbon, pyrite, and other metallic sulphides, may be found in sufficient concentration in the soil or rock to make it conductive. In massive metallic ores, when the metallic grains are connected, the current flows via the electrons contained in the metal.

The range resistivities is very large. The values given in Figure 1 are only informative: the particular conditions of a site may change the resistivity values. For example, dry coarse sand or gravel may have a resistivity like that of igneous rock, whereas weathered rock may be more conductive than the soil overlying it. Since the resistivity of a soil or rock is controlled primarily by the pore water conditions, there are wide ranges in resistivity for any particular soil or rock type, such that resistivity values cannot be directly interpreted in terms of soil type or lithology. Commonly, however, zones of distinct resistivity can be associated with specific soil or rock units on the basis of local outcrops or borehole information. It is the enormous variations in rock and mineral electrical resistivity that makes resistivity techniques attractive.

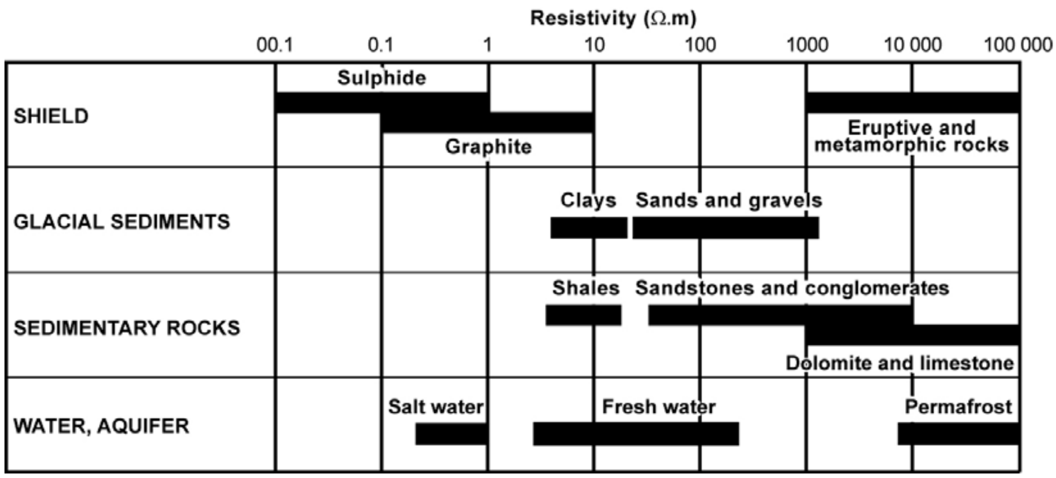

Figure 1: Resistivity of rocks (modified from Marescot, 2006)

Basic theory of electrical prospecting

Consider a single point electrode A located on the surface of a semi-infinite electrically homogeneous medium (Figure 2). Equipotential surfaces are shells surrounding the current electrodes on which the electrical potential is everywhere equal. Current lines represent a sampling of the infinitely many paths followed by the current; these paths must be everywhere normal to the equipotential surfaces. The effect of an electrode pair (A the current source and B the current sink) can be found by superposition, such that the added effect of individual current electrodes yields the final value for the potential field. In addition to the two current electrodes, a second pair of electrodes (M and N) is used, between which the potential difference ΔV is measured. The potential field decreases rapidly away from the current electrodes. The current and potential electrodes can be interchanged without affecting the results. This property is called reciprocity.

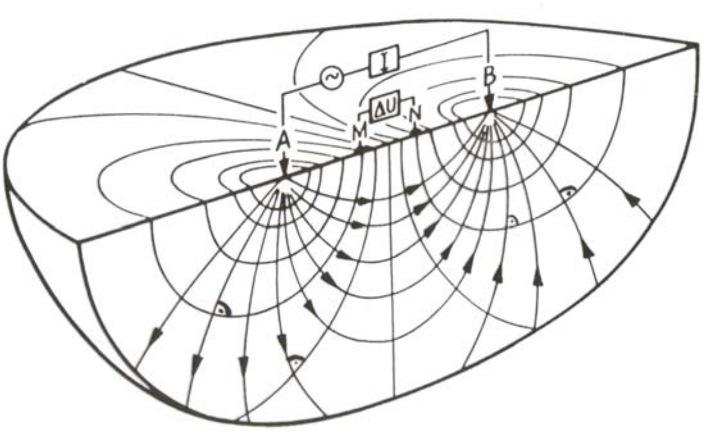

Figure 2: Equipotential surfaces and associated current lines for two current electrodes

A variety of electrode arrays or spreads (2, 3 or 4 electrodes) are commonly used (Figure 3). For some arrays (e.g. the pole-pole or pole-dipole), one or two electrodes are installed remotely (theoretically at "infinity")

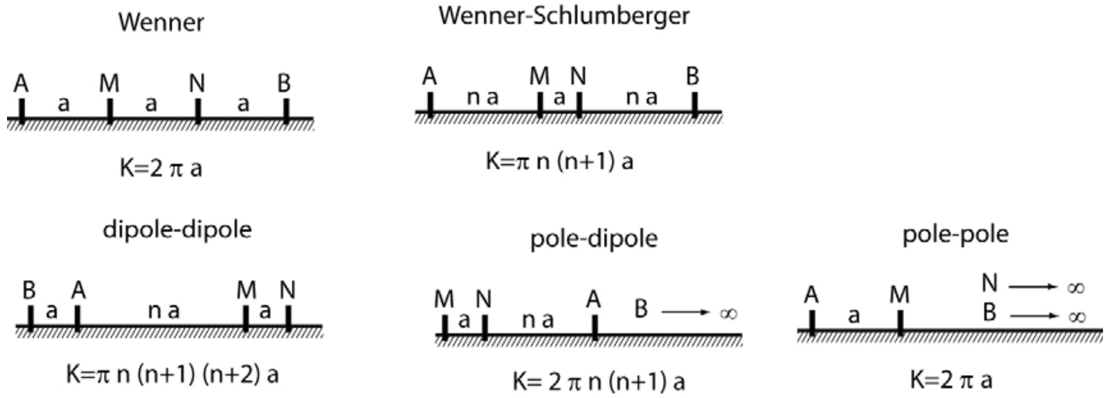

Figure 3: Electrode arrays frequently used in surface electrical prospecting (modified from Marescot, 2006)

The resistivity of a medium can be estimated from the measured values of ΔV (in Volts), the current I (in Amperes), and the geometric factor K (in m), where K is a function only of the geometry of the electrode arrangement and the geometry of the investigated structure (e.g. a half space for measurements collected on the earth surface). The basic equation for resistivity prospecting is given by:

$$\rho_{app} = K \frac{\Delta V}{I} \qquad \text{Eq. 1}$$

Wherever these measurements are made over a heterogeneous earth, the data from resistivity surveys are defined as apparent resistivities. Apparent resistivity is defined as the resistivity of an equivalent electrically homogeneous and isotropic half-space that would yield the potential measured on the heterogeneous earth using the same applied current with the same arrangement and spacing of electrodes. The apparent resistivity is equal to the true resistivity of the ground only if the earth is homogeneous. We note also that topography has an influence on the measured apparent resistivity. The resistivity surveying problem is then the use of apparent resistivity values from field observations at various locations and with various electrode configurations to estimate the true subsurface resistivity distribution at a site.

For current electrodes located below the surface (i.e. borehole electrodes), the definitions of K given in Figure 3 are no longer valid and a more general definition must be used (Eq. 2). This definition is based on an analogy with optics that allows equivalent images for the current electrodes (see Figure 4) to be evaluated:

$$K = \frac{4\pi}{\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN} + \frac{1}{A'M} - \frac{1}{A'N} - \frac{1}{B'M} + \frac{1}{B'N}} \qquad \text{Eq. 2}$$

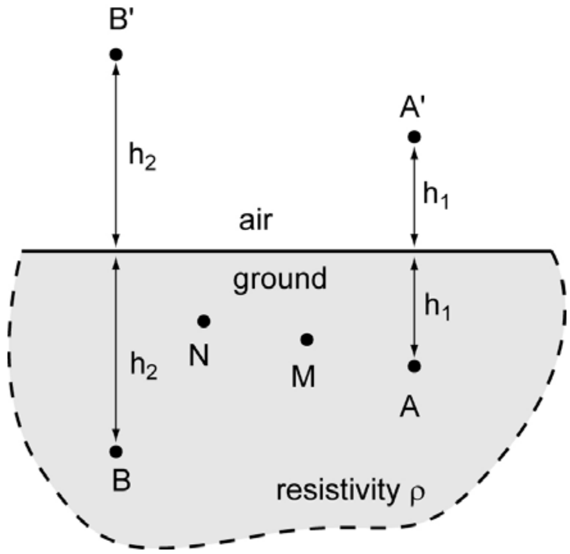

Figure 4: Electrode array frequently used in surface electrical prospecting (modified from Marescot, 2006)

Note that the equations in Figure 2 can be obtained from a simplification of Eq. 3 for electrodes at the surface.

Depth of investigation

For the same electrode spacing and a two-layer earth, the current mainly flows in the first layer if it is more conductive than the second, and vice versa. Moreover, for small electrode spacings, the apparent resistivity is close to the surface layer resistivity, whereas at progressively larger electrode spacings, the apparent resistivity approaches that of the second layer. The asymptotic behaviour of variations in apparent resistivity differs according to the relative resistivities of the two layers. Accordingly, there is therefore no simple relationship between electrode spacings and interface depths. Instead the depth of investigation depends on the resistivity contrasts and can be only formally defined for an homogeneous earth. Typically, the maximum distance between current electrodes should be three or more times (sometimes ten) the depth of interest to assure that sufficient data have been obtained.

Instruments and measurements

Current injection

A direct or low-frequency alternating current is applied to the current electrodes and the current is measured with an ammeter. Current electrodes are generally stainless steel stakes. They must be driven far enough into the ground to make good electrical contact. If the contact is poor and the injected current small, the quality of measurements will be degraded (sensitive to noise). One common difficulty is the high contact resistance between the current electrodes and soil or rock. This problem can sometimes be alleviated by pouring salt water around the current electrodes or adding electrodes in parallel. If the problem is due to a combination of high earth resistivity and large electrode spacing, the remedy is to increase the input voltage across the current electrodes. Power is usually supplied by dry cell batteries in series in smaller instruments and motor generators in larger instruments. Between 90 V and several hundred volts may be used in surveys for engineering purposes.

Although current electrodes are affected by contact resistances, the actual values are not important as long as sufficient current is injected into the ground and the values are not greatly different at the two electrodes. Contact resistance influences the relationship between current and potential at the current electrodes, but because only the measured value of current is used, the potentials on these electrodes do not figure in the theory or interpretation. Typical currents in instruments used for engineering applications range from 2 mA to 500 mA.

Potential measurement

Potential differences ΔV are measured by a voltmeter attached to the potential electrodes. Ideally, no current should flow between the potential electrodes. This is accomplished by using a very high input impedance operational amplifier. One advantage of the four-electrode method is that measurements are not sensitive to the contact resistances at the potential electrodes, as long as they are low enough that a measurement can be made; the system is adjusted to ensure that no current flows in the potential electrodes during the measurements. With zero current, the actual value of contact resistance is immaterial, since it does not affect the potential. Note, that the ammeter and voltmeter are grouped together in a device called a resistivity meter.

External influences on measurements

Telluric currents are naturally occurring electric fields that are widespread, some being of a global scale. They are usually of small magnitude, but may be very large if supplemented by currents of artificial origin. Spontaneous potentials may be generated in the earth by galvanic phenomena around electrochemically active materials, such as pipes, conduits, buried scrap material, cinders, and ore deposits. They may also occur as streaming potentials generated by groundwater movement. Electric fields associated with groundwater movement have the highest amplitudes where groundwater flow rates are high, such as through subsurface channel flow. The effects of telluric currents and spontaneous potentials can be cancelled by using slowly alternating currents. This strategy can also be used to eliminate the influence of potential electrode polarization, because the polarized ionization fields do not have sufficient time to develop in a half-cycle, and the alternating component of the response can be measured independently of any superimposed direct currents. The frequencies used are very low, typically below 20 Hz, so that the measured resistivity is essentially the same as the direct current resistivity. The average values of V and I for the forward and reverse current directions are used to compute the apparent resistivity. An alternative technique is to use non-polarizing electrodes to measure the potential (see lecture on Spontaneous Potential).

Resistivity measurements can also be affected by metallic fences, rails, pipes, or other conductors, which may provide short-circuit paths for the current. The effects of such linear conductors can be minimized, but not eliminated, by deploying the electrode arrays along lines perpendicular to the conductors. Also, electrical noise from power lines, cables, or other sources may interfere with the measurements. Rejection filters for defined frequencies (16-20 Hz, 50-60 Hz) are now common in modern instruments. Sometimes, electrical noise originates from temporary sources (e.g. of an industrial origin), so better measurements can be made by waiting until conditions improve (e.g. during the night). Modern resistivity instruments are capable of data averaging or stacking; this allows resistivity surveys to proceed in spite of noisy site conditions and to improve signal-to-noise ratio for weak signals.

Survey strategies and interpretation

An array with constant electrode spacing can be used to investigate lateral changes in apparent resistivity that reflect lateral variations in the geology or hydrology. To investigate changes in resistivity with depth, the electrode spacing needs to be varied; apparent resistivities are affected by material at increasingly greater depths as the electrode spacing is increased. By deploying numerous (ten's to hundred's of) electrodes along lines or across an area, it is possible to estimate variations in resistivity in all directions. This technique, known as electrical resistivity imaging or tomography (ERT), produces images of 2D or 3D features in the subsurface. ERT is currently the most used electrical resistivity technique for surveying from the surface or between boreholes.

Constant separation traversing (resistivity mapping)

In this technique, a series of profiles (or a map) of apparent resistivities is obtained by moving an array with constant electrode spacing. In this case, the depth of investigation is kept approximately fixed and lateral changes in the subsurface are investigated. To map larger areas, modern mobiles systems, sometimes towed behind small vehicles, can be used. This technique only provides qualitative information about the repartition of resistivity in the subsurface.

Surface Electrical Resistivity Tomography

Two dimensional electrical imaging is usually carried out using a large number of electrodes, typically set up along a straight line (Figure 5). In this case, it is necessary to assume that resistivity does not change significantly in the direction perpendicular to the survey line (2D models). Normally, a constant spacing between the electrodes is used. The electrodes are linked by a multi-core cable and connected to a switching unit and a resistivity meter. The whole survey can be controlled with a laptop computer, such that the user can program a sequence of resistivity measurements. This sequence (several hundreds) of measurements along the line is made using different electrode spacings and based on some predefined electrode arrangements (e.g. Wenner, Schlumberger, dipole-dipole, pole-dipole). By increasing the distance between the electrodes, the effective depth of investigation is increased.

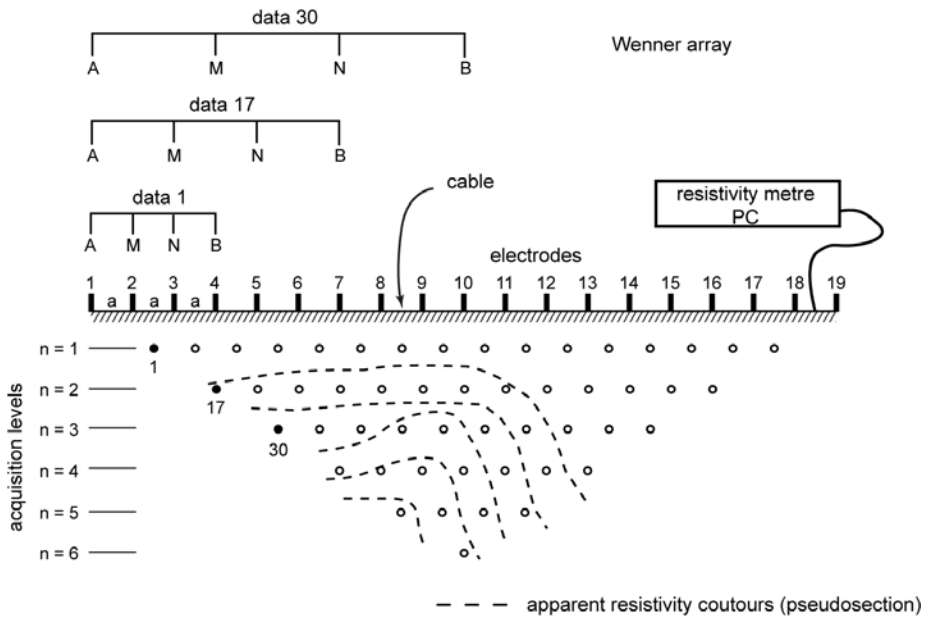

Figure 5: Principle of 2D electrical resistivity tomography and pseudosection (modified from Marescot, 2006)

The laptop computer automatically selects the appropriate electrodes for each measurement in the programmed sequence (Figure 5) and records the measured apparent resistivities. For quality control, the data are often displayed as pseudosections; in a pseudosection, each apparent resistivity value is plotted at a distance along the profile that corresponds to the middle of the array and at a depth proportional to the electrode spacing (pseudo-depth) or alternatively that correspond to the acquisition level. Since apparent resistivity varies in a smooth manner, an erroneous data value would stand out in a pseudosection. Pseudosections are a convenient way of plotting the data. They are not images of the true subsurface resistivities, because they depend on the particular electrode array used! A pseudosection based on measurements made using a Wenner electrode configuration is quite different from a pseudosection based on a dipole-dipole configuration. Therefore, a pseudosection should not be interpreted without processing (or inversion, see below).

An example of a Wenner apparent resistivity pseudosection for a simple synthetic model is displayed in Figure 6. For this case, 35 electrodes are used. The model represents a large conductive zone (10 Ωm) and two small resistive heterogeneities (500 Ωm) embedded in a 100 Ωm medium. Clearly, there is very poor correlation between the true model and the pseudosection. In particular, the two 500 Ωm blocks cannot be identified in the pseudosection. The processing (inversion) should allow these features to be recovered.

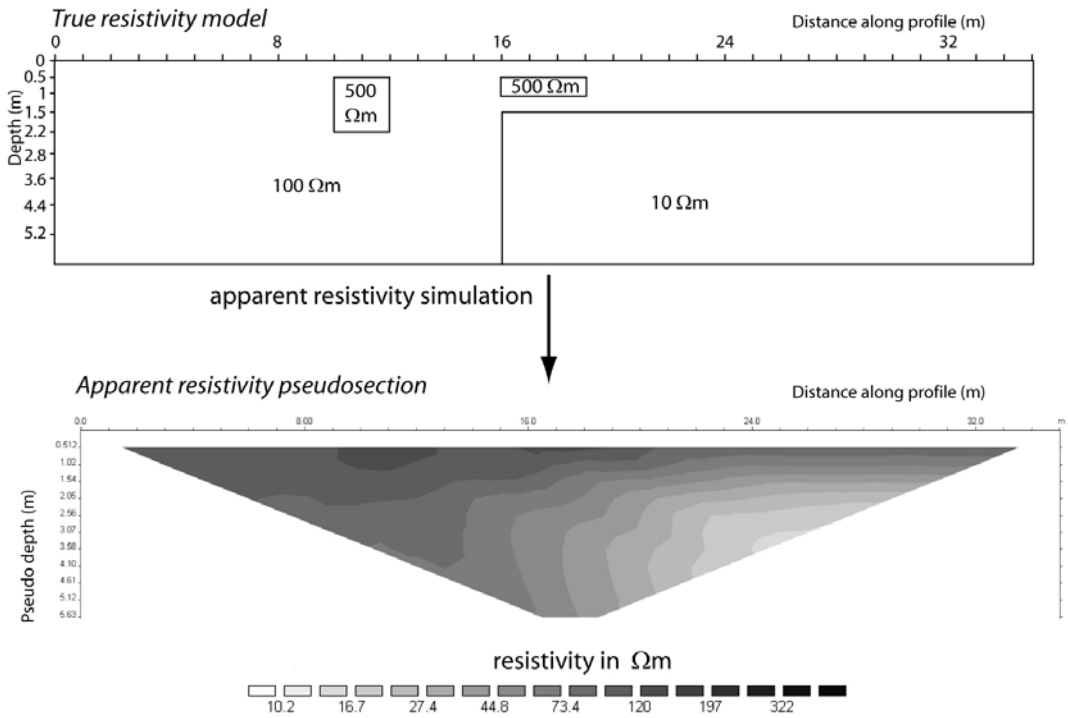

Figure 6: Example pseudosection for a simple resistivity model (modified from Marescot, 2006)

A 3D approach is required at locations where the geology cannot be approximated as 2D. A grid of electrodes is used to investigate changes in resistivity in all directions (Figure 7). The pole-pole or pole-dipole electrode configurations are preferred for 3D surveying. Generally, 3D surveying is generally more time consuming than 2D surveying and special 3D resistivity inversion software is required.

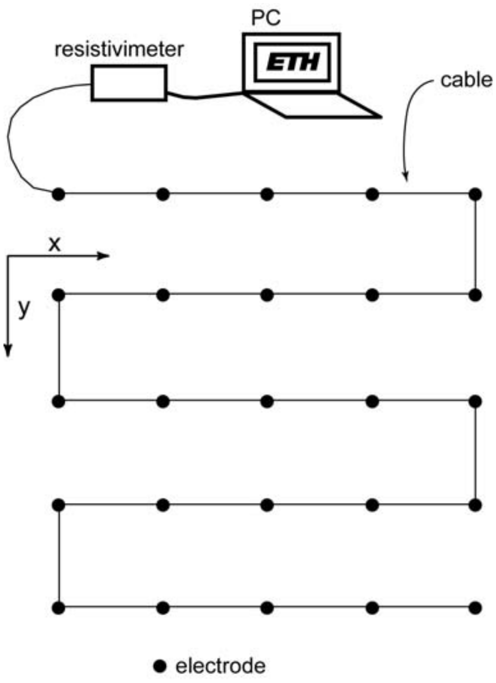

Figure 7: Example of 3D surface electrical tomography (Marescot, 2005-2007)

Borehole Electrical Resistivity Tomography

Data acquisition strategies for borehole studies are similar to those used for surface investigations. The use of borehole electrodes increases the resolution at depth. In crosshole resistivity tomography, lines of electrodes are located within pairs of boreholes. An example of a crosshole pole-pole electrode arrangement is illustrated in Figure 7.

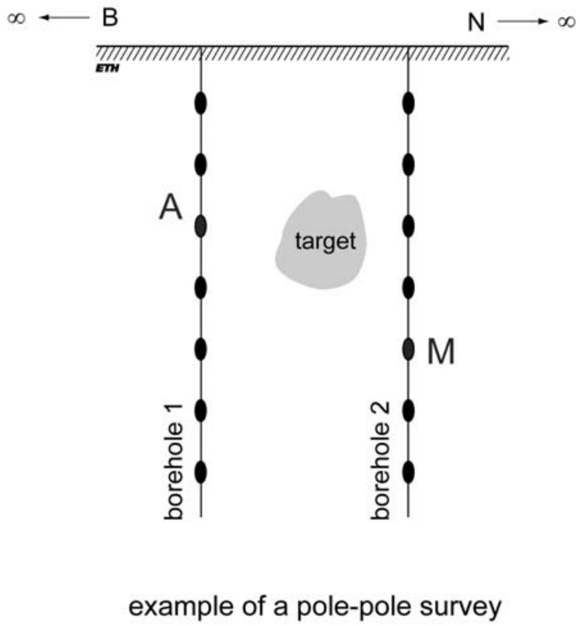

Figure 7: Example of a crosshole pole-pole survey. An example for the locations of electrodes A and M is illustrated (Marescot, 2005-2007)

In crosshole resistivity measurements, it is necessary to ensure good electrical contact between the electrodes and the borehole walls. This is not a problem when working in the saturated zone, where the electrode is in contact with water. In this case, the borehole pipe should be made of screened (slotted) PVC tubes to allow the electrical current to flow into the ground. Metallic tubes or non-screened PVC tubes preclude the use of this technique. Working in the vadose zone requires extra effort with special equipment (e.g. a ring of electrodes attached to the outside of the PVC tube).

Measurements made in boreholes cannot generally be plotted as pseudosections, so alternative quality control methods are required. As for surface surveys, an inversion program is used to process the data.

Inversion and interpretation

Once the data (apparent resistivities) are collected, an inversion scheme is used to estimate the subsurface resistivity properties. In this scheme, a model is sought that explains in an optimal manner the data measured in the field. To represent resistivities in the subsurface, the model is a discretized into a series of blocks with constant resistivities (*M* blocks in Figure 8). The inversion scheme is aimed at determining the resistivities of the individual blocks from the measured apparent resistivities. In 3D, the blocks are volume elements.

A basic model is first created, starting from a priori information entered by the user (Figure 8). In step 1, the algorithm calculates the response of this model using a numerical modelling technique (e.g. a finite-element or finite-difference method). Then, the algorithm determines the difference (error) between the model response and the data observed in the field according to a certain criterion (step 2). The model is then modified (updated) with the aim of minimizing this difference. Then update equation is often based on a Gauss-Newton algorithm (see lecture introducing inversion techniques). The operation is then iteratively repeated until the process converges (i.e. the error does not decrease significantly any more). The final result is displayed with a definite colour for each block or using contour lines of equal resistivities. After inversion, the final result should be a reliable image of the subsurface that represents the geology and hydrology. In the example displayed in Figure 8, the large conductive zone and two small resistive blocks displayed in the model of Figure 6 are well imaged.

Once an image of the subsurface is obtained, interpretation can be carried out using priori knowledge about the geology/hydrology. Only with such knowledge, would we be able to identify the source of the 500 Ωm anomalies in Figure 8, for example. Like all potential and diffusive field methods, the value of a measurement obtained at any location represents a weighted average of the effects produced over a large volume of material, with the nearby portions contributing most heavily. This means that the electrical resistivity method does not have the high resolution capabilities of the wavefield (i.e. seismic and georadar) techniques. There is another feature common to all potential and diffusive field geophysical methods: a particular distribution of potential at the surface does not have a unique interpretation. While these limitations should be recognized, the non-uniqueness or ambiguity of the resistivity method may be less than with some other geophysical methods (e.g. gravity, magnetic or self potential), since we have a direct control on the source in this case. Nevertheless, it is always advisable to use several complementary geophysical methods in an integrated exploration program rather than relying on a single method.

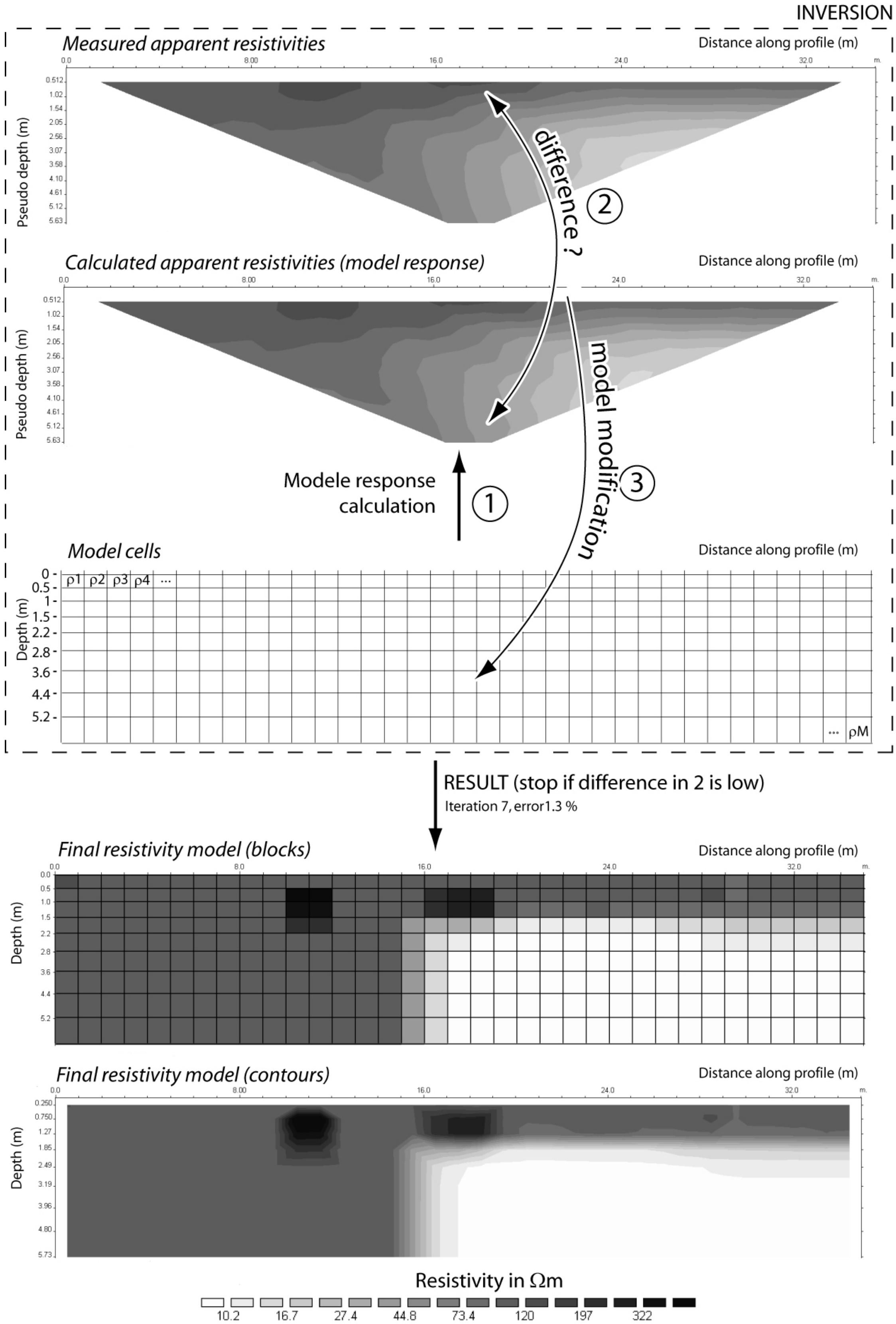

Figure 8: Principle of resistivity inversion (modified from Marescot, 2006)

Internet links

The following internet links provide modelling and inversion programs (partially free) for the processing of electrical resistivity tomography data:

http://www.geoelectrical.com/
http://www.geol.msu.ru/deps/geophys/
http://www.es.lancs.ac.uk/es/people/teach/amb/

Two useful links containing course notes on electrical resistivity techniques:

http://www.tomoquest.com
http://www.aug.geophys.ethz.ch/teach/iuugeophysik/iuugeophysik.html
http://www-ig.unil.ch/cours/

Link providing useful indication on the limitations of the geophysical techniques:

http://www.gr.sgpk.ethz.ch

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