Cambridge University Press
978-1-107-01927-0 - The Self-Potential Method: Theory and Applications in Environmental Geosciences
André Revil and Abderrahim Jardani
Excerpt
More information

1

Fundamentals of the self-potential method

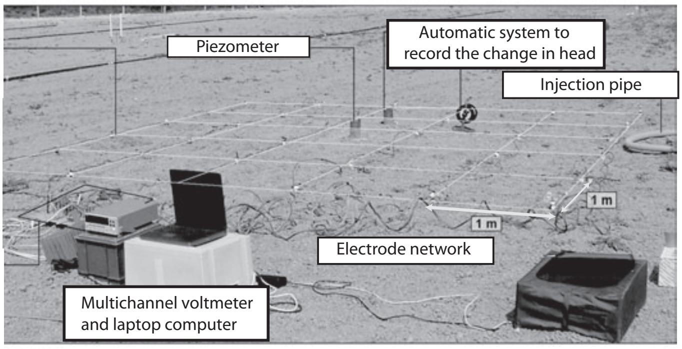
The self-potential method is a passive geophysical method, like the gravity and magnetic methods. It involves the measurement of the electric potential at a set of measurement points called self-potential stations. The sampled electrical potential (or electrical field) can be used (inverted) to determine the causative source of current in the ground and obtain important information regarding ground water flow, hydromechanical and geochemical disturbances. In this chapter, we discuss the principle of the measurements, strategies to map or monitor the self-potential field and the origins of spurious signals. We also provide a short overview of the electrical double layer coating the surface of the minerals. Indeed, a good understanding of the electrical double layer is of paramount importance in the study of self-potential signals. We also provide a short overview of the history of the self-potential method.

1.1 Measurements

1.1.1 Equipment

Self-potential measurements are performed using non-polarizing electrodes connected to a voltmeter. For example, Figure 1.1a shows a multichannel voltmeter used to record the voltage of 80 non-polarizing electrodes at a frequency of one sample per minute. A non-polarizing electrode is formed by a metal in contact with its own salt (e.g., silver in a silver chloride solution, or copper in a copper sulfate solution). An example of non-polarizing electrode, the Petiau $Pb/PbCl_2$ electrode, is shown in Figure 1.1b. The difference of the electric potential between two electrodes is measured by using a voltmeter with a high sensitivity (at least 0.1 mV), and high input impedance (typically ∼10–100 MOhm, for soils to 1000 GOhm on permafrost). Figure 1.1c shows the record of the electrical potential difference between one electrode, located close to an injection well, and a reference electrode,

(a) Typical self-potential acquisition system



(b) Petiau electrode

(c) Typical raw self-potential response to pumping test

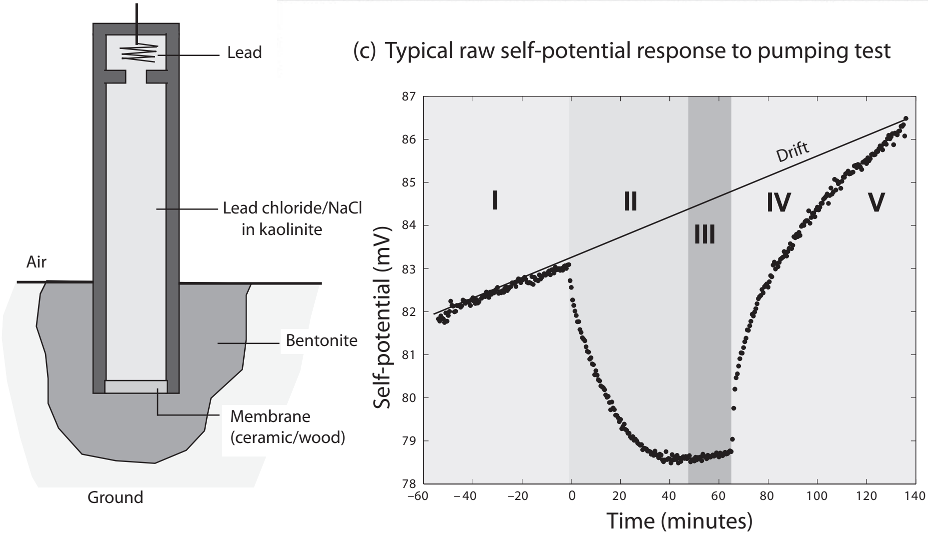


Figure 1.1. Typical recording system to monitor the self-potential response associated with a pumping test. (a) Picture showing the network of electrodes and the recording multielectrode voltmeter. (b) Petiau non-polarizing electrodes. (c) Typical raw data for the self-potential (modified from Jardani *et al.*, 2009a). Phase I corresponds to the data obtained prior to the start of the pumping test; II is the transient phase during pumping; III is the steady-state phase; IV is the rapidly changing portion of the recovery phase; and V corresponds to the slowly changing to steady-state portion(s) of the recovery phase. The line shows the drift of the potential of the scanning with respect to the reference electrodes (both electrodes experiencing different temperatures over time). Before being analyzed, these data need to be detrended, filtered, and shifted in such a way that the potential prior to the start of pumping ($t = 0$) is equal to zero for each electrode (static removal).

located several tens of meters way (further than the radius of influence of the well). The data are the raw (unfiltered) data. We can see the self-potential response associated with the pumping test and the recovery following the shutdown of the pump. In other words, the self-potentials are remotely sensitive to the ground water flow

Cambridge University Press
978-1-107-01927-0 - The Self-Potential Method: Theory and Applications in Environmental Geosciences
André Revil and Abderrahim Jardani
Excerpt
More information

triggered through the pumping test, a point that makes the self-potential method a non-intrusive flow sensor.

To perform accurate self-potential measurements, the impedance of the voltmeter has to be at least ten times higher than the impedance of the ground between the two electrodes, in order to avoid leakage of current in the voltmeter. A voltmeter with an internal impedance of 100 MOhm would be high enough for most applications. However, working over very resistive materials ($>$100 000 Ohm m, e.g., ice, permafrost, crystalline rocks) requires the use of a voltmeter with much higher internal impedance (some voltmeters can be made with an internal impedance of 10^{12} Ohm). The voltmeter, like all instrumentation in geophysics, has to be calibrated regularly against known resistances to check its accuracy over a broad range of resistance values.

1.1.2 Self-potential mapping

The oldest approach in self-potential is to establish a map of the distribution of the electrical potential at the ground surface. In this case, a reference electrode is used as a fixed base, and the second electrode is used to scan the electric potential at the ground surface. The fixed (reference) electrode is kept in a small hole filled with bentonite mud. Because the presence of the mud modifies the electric potential at the contact between the electrode and the ground, the potential of this station is arbitrary, and should not be used as a point (with zero potential) in performing the self-potential map. Adding salty water to improve the coupling between the electrode and the ground should be also avoided, especially for monitoring purposes, because evaporation of the water changes the salinity of the pore water, generating spurious potential changes over time in the vicinity of the surface of the electrodes. These spurious potentials are due to diffusion potentials that will be explored further in Chapter 2. The roving (scanning) electrode is used to measure the electric potential at a set of stations, referenced in space with a GPS (2 m accuracy in x and y is usually good enough for most applications). Both prior to and after the measurements, the difference of voltage between the reference electrode and the scanning electrode has to be checked by putting the electrodes one against the other, contacted through their porous membranes (for instance in Figure 1.1b, the porous membrane is made of wood), and measuring the difference in electrical potential. The drift of the voltage between the electrodes should be kept as small as possible over time (e.g., < 2 mV per day is an acceptable drift for self-potential mapping). The potential map is, therefore, a map relative to the (unknown) potential at the base station. Actually, like all scalar potentials in physics, the self-potential is defined to an additive constant. Only the electric field (which is the gradient of the electric potential in the low-frequency limit of the Maxwell

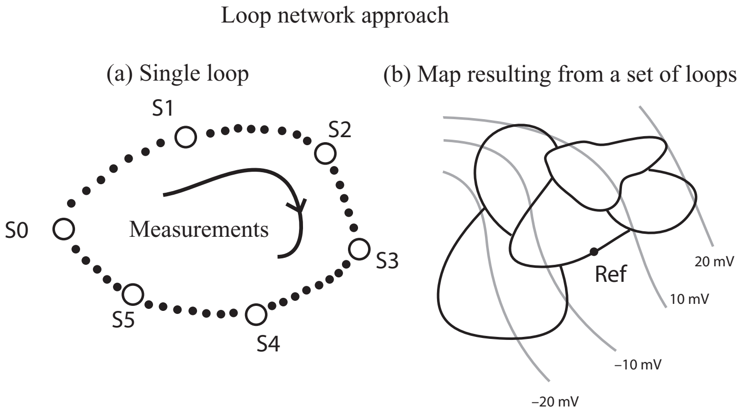


Figure 1.2. Large-scale self-potential mapping over the ground surface using a close loop approach combined with the leap-frog approach. (a) Sketch showing a single loop. S0 denotes the first base station. Measurements are performed along the self-potential stations characterized by the small black circles. At some point, a new base station is established S1 and so on. The potential distribution can be reconstructed along the loop respecting the fact that the self-potential loop should be closed. The value at S0 should be close to zero. If this is not the case, a closure error should be applied to the data to "close the loop." (b) A self-potential map is built by combining the information on several loops and using one of the base stations as reference for the entire map. The black plain lines denote the self-potential loops while the gray lines denote the electrical equipotentials obtained for instance by kriging the self-potential data.

equations) is well-defined. At the interface between the ground and the atmosphere, the electric field is tangential to the ground surface, because air can be considered as an electric insulator. A tutorial, made by S. Barde Cabusson and Anthony Finizola on data reduction for self-potential mapping is provided on the website associated with this book (file SP_Processing_tutorial, provided with permission of the authors).

For large-scale mapping of the self-potential, several strategies are possible. The first has been used by numerous researchers: one base station is chosen as the reference and measurements are performed with scanning electrodes at different secondary stations. To extend the measurement array, the initial base station is removed and the reference electrode is transplanted, or "dropped," at the position of the last measurement station (a leap-frog approach can be used instead). This operation is repeated to close a loop. This approach is called the loop network. The circulation of the electrical field should be zero along a closed loop performed at the ground surface; in other words, the sum of the drop potentials along a closed loop is zero. This strategy is described in Figure 1.2. It is very important to close the loop when making self-potential measurements, in order

Cambridge University Press
978-1-107-01927-0 - The Self-Potential Method: Theory and Applications in Environmental Geosciences
André Revil and Abderrahim Jardani
Excerpt
More information

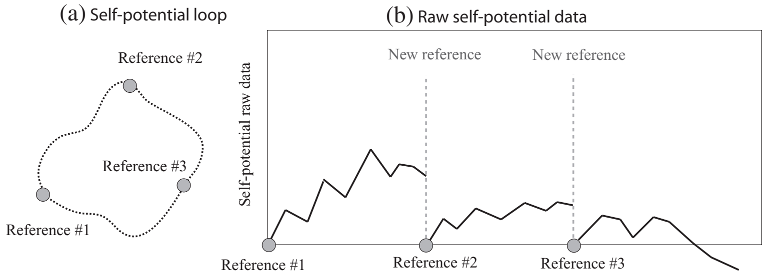


Figure 1.3. Typical self-potential profile along a closed loop with a total of three base stations used as references. (a) Closed loop. (b) Raw self-potential profile (modified from Barde-Cabusson and Finizola, 2012, unpublished material, see file SP Processing_tutorial, provided with permission of the authors).

to check the closure error (due to the propagation of errors in the changes of the reference electrode) and to correct the self-potential measurements from this closure error. If this is not done, there is a risk of accumulating errors toward the end of the profiles (some published self-potential maps in volcanic areas clearly show huge accumulated errors at the end of profiles that were misinterpreted as ground water flow pattern). An example of application of the loop approach to map the large-scale self-potential anomalies downstream a landfill can be found in Naudet *et al.* (2003, 2004). An excellent description of the procedure of self-potential mapping and reduction of closure errors can be found in Minsley *et al.* (2008).

The corrections along a close loop with several changes of self-potential base stations are explained in Figures 1.3 and 1.4. In Figure 1.3, we show that the self-potential measurements are by nature discontinuous each time a base station is used (the potential at the base station is setup to zero). The first correction is naturally to reestablish the continuity of the electrical potential using the first base station of the profile as a global base station for the entire loop. The final step is to correct for the closure error along the loop as mentionned above.

A completely different strategy for self-potential mapping is called the "star network." In this approach, we first determine the difference of potential between a set of base stations separated from each other by several hundred meters (up to a kilometer, see Figure 1.5). As the wires used to measure a difference of potential between two points of the Earth are usually not shielded, they can be subject to induction effects; some fluctuations in the readings are typically observed when the cable used for the measurements is too long. In subsequent steps, each base station is used as the local reference of profiles that are more or less radially distributed about this station. This approach was, for instance, followed by Fournier (1989) to get a large-scale self-potential map over tens of square kilometers.

Cambridge University Press
978-1-107-01927-0 - The Self-Potential Method: Theory and Applications in Environmental Geosciences
André Revil and Abderrahim Jardani
Excerpt
More information

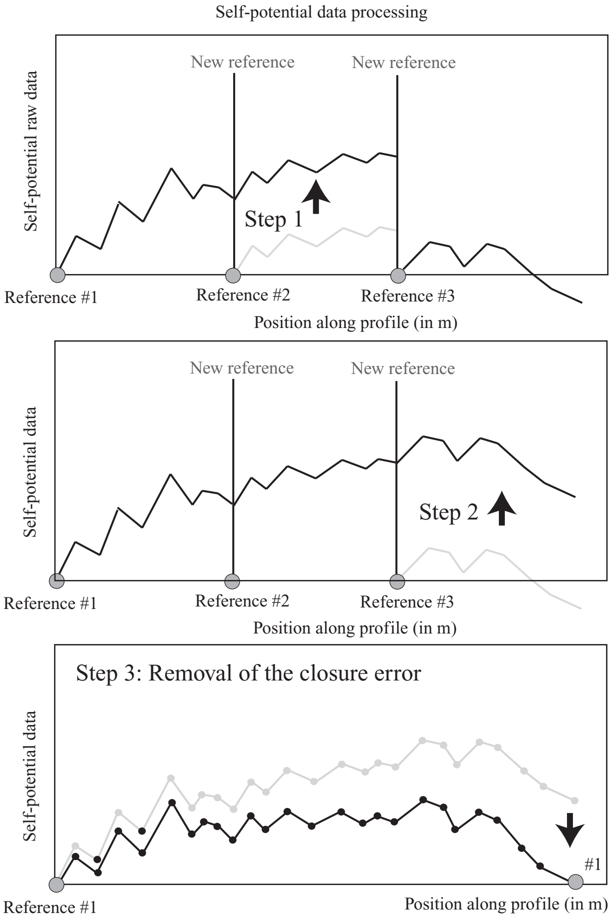


Figure 1.4. The corrections for the raw self-potential profile along a closed loop involve a series of steps. In the first set of steps, the potential is set continuous at each change of base station. The final step corresponds to the closure error (modified from Barde-Cabusson and Finizola, 2012, unpublished material, see file SP Processing_tutorial, provided with permission of the authors).

A third strategy, which has been used rarely in the literature, is to directly measure the electrical field (not the electrical potential) at a set of stations (Figure 1.6). However, measuring the first spatial derivative of a noisy field can be difficult, as the gradient measurement may amplify the noise. The electrical field can be measured at a station P by measuring the potential difference in two normal directions. The electrical field due to a buried current source is tangential to the ground surface. In order to get a reliable estimate of the electrical field at this point, it is necessary to average the estimated electrical field magnitude over a set of several points. This method does not require long wires and is easy to carry out

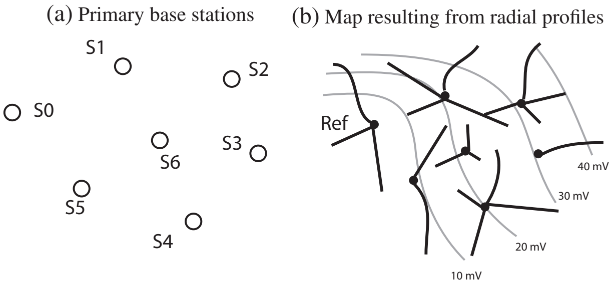


Figure 1.5. Large scale self-potential mapping using a star approach. (a) A set of base stations is chosen and prepared with bentonite plug setup in the ground. The difference of potential between these stations is measured. (b) Each of these stations is used as a secondary reference and radial profiles are performed from this station. The self-potential map is built by using one of the base stations as a reference for the entire survey. The black plain lines denote the self-potential profiles from the base stations while the gray lines denote the electrical equipotentials obtained for instance by kriging the self-potential data.

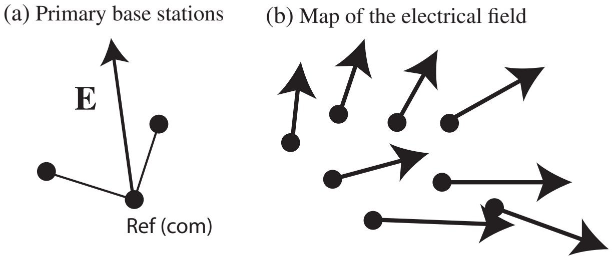


Figure 1.6. Large-scale mapping of the electrical field. (a) Each station is formed by three measurement points (L shape) to determine the two components of the electrical field, which is locally tangential to the ground surface. (b) Such a pair of measurements is repeated at various stations at the ground surface of the Earth and a map of the electrical field (a vector map) is built. Note that this approach is reference free but the electrical field can be very noisy.

in the field. However, a careful check of the reliability of the measurements is necessary to avoid interpreting spurious effects, especially associated with the very heterogeneous nature, in terms of resistivity distribution, of the shallow subsurface.

Any fieldwork requires the use of a good notebook (if possible waterproof), in which all information pertaining to the survey is recorded. This includes weather conditions (both during and prior to the survey), the position of the self-potential stations (using GPS, for instance), the value of the self-potential data, and any notes pertaining to understanding the survey, including a description of the equipment

Cambridge University Press
978-1-107-01927-0 - The Self-Potential Method: Theory and Applications in Environmental Geosciences
André Revil and Abderrahim Jardani
Excerpt
More information

and any technical difficulties met during the survey. The notebook should also include some basic drawings of the profiles and, if possible, some printed pictures taken during the survey. After the completion of a day working in the field, it is recommended to take pictures of the relevant pages of the notebook, store the information in a memory stick and store the memory stick in a safe place.

1.1.3 Self-potential monitoring

It is possible to use the self-potential method as a monitoring method to track the changes of variables of interest like the Darcy velocity, the moisture content, and salinity. We will show numerous examples of self-potential monitoring in this book, for a variety of problems, especially in Chapters 5–8. In monitoring applications, a multi-electrode array is connected to a multichannel or multiplexed voltmeter, as shown in Figure 1.1a, and distributed along the Earth's surface over a target of interest. This approach is completely analogous to what is done in electroencephalography, for medical applications. In electroencephalography, a network of electrodes is used to monitor the change in the distribution of the electric potential on the scalp in order to localize the active part of the brain where electrical currents are manifested along the synapses between neurons; see Grech *et al*. (2008). Even if the electrical potentials are measured at several hundred hertz in electroencephalography, the same fundamental (quasi-static) elliptic equation applies as discussed below in Section 1.3. Because the main sources of currents in the ground are closely connected to the existence of the electrical double layer at the pore water–mineral interface, we discuss this electrical double later in the next section (Section 1.2). Some important, relevant publications about this methodology applied to the long-term monitoring of a site include Perrier *et al*. (1998) and Trique *et al*. (2002).

1.1.4 Electrode drift

The potential of the electrodes is always temperature dependent. Even the Petiau Pb/PbCl$_2$ electrodes have non-negligible temperature dependence on the order of 0.2 mV °C^{-1} despite the fact that they were designed to minimize such effect. Indeed, other non-polarizing electrodes have, easily, a temperature dependence comprised between 1 and 2 mV °C^{-1}. This has many implications for both mapping and monitoring. In the case of self-potential mapping, having a reference electrode in the cold ground and scanning the potential at the ground surface with a warmer electrode (e.g., one held in a hand) can easily generate a difference of potential higher than 10 mV. In these cases, the voltage of the reference electrode should not be used in building a self-potential map as already mentioned above. Measures

Cambridge University Press
978-1-107-01927-0 - The Self-Potential Method: Theory and Applications in Environmental Geosciences
André Revil and Abderrahim Jardani
Excerpt
More information

should be taken to avoid such a temperature differential between the electrodes; for instance, the scanning electrode can be attached to a stick avoiding direct contact between the scanning electrodes and the hands. The temperature of the inner part of the electrode can be measured and a temperature correction can be applied.

In monitoring, the shallow subsurface is always characterized by diurnal temperature variations in the ground down to 30–50 cm. Hence, the monitoring electrodes should be installed at a depth of 30–50 cm, or temperature sensors need to be utilized in the vicinity of the electrodes to apply a post-correction of the effect of the temperature. Burying the electrodes has several advantages, as it limits the influence of external electromagnetic noise (sensitivity decreases rapidly with depth), reduces the risk of desiccation, and avoids the spurious electrical signals associated with the roots of vegetation. The drift shown in Figure 1.1c was due to a variation of temperature between one of the monitoring electrodes and the reference electrode during a transient hydraulic pumping test in Boise (Idaho, USA) in June 2007.

For both mapping and monitoring, it is strongly recommended to avoid the use of salty water. The presence of salty water between the electrodes and the ground creates a highly variable, localized diffusion potential that is hardly the same from one place to the other. To make matters worse, this potential is expected to change with time, because of the drying of the saline solution and the concomitant increase in salinity. Our experience indicates that the use of salty water yields unreliable self-potential mapping, and that unpredictable changes and drifts in the recorded potentials are observed during monitoring. For mapping, it is much better to dig a small hole until the presence of moisture is recognizable by visual inspection, and firmly apply the end-face of the electrode against the ground. The contact resistance can be measured with the voltmeter from time to time, to check that the resistance of the ground between the reference electrode and the scanning electrodes remains low, with respect to the internal impedance of the voltmeter. Bentonite (silt and smectite powder) can be used at each station, usually the stations need to be prepared at least 10 minutes before the measurements in order to stabilize. The advantage of bentonite is that it will keep the potential drop between the electrodes and the ground constant in space and time (in this case the potential drop between the bentonite and the electrode is called a membrane potential and it is always constant). Figure 1.7 shows two profiles. The first profile (Figure 1.7a) indicates the level of repeatability expected in the field under normal conditions. The second profile (Figure 1.7b) shows a discrepancy between the prediction of a model, based on the computation of the ground water flow, and the measured self-potential profile. This discrepancy was due to a problem with the scanning electrode that was not in thermal equilibrium with the ground (and the reference electrode) at the beginning of the survey.

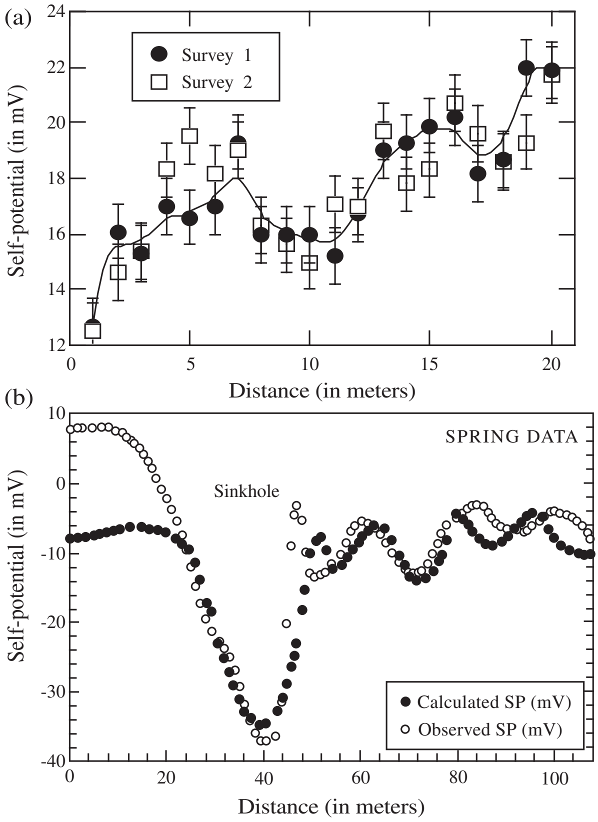


Figure 1.7. Example of high resolution self-potential profile. (a) Repeat of a high resolution self-potential survey. The repeatability is better than 2 mV. The electrodes were just put in contact with the ground after a small hole was dug. (b) High resolution self-potential (SP) survey associated with a sinkhole. Note the discrepancy between the model-predicted and measured self-potential values at the beginning of the profile. Thermal equilibrium between the reference and scanning electrodes was not reached at the beginning of the profile. Modified from Jardani *et al*. (2006a).

In some cases, it may be necessary to reoccupy exactly the same stations in order to accurately repeat a profile or a map over weeks, months or years. In this case, the best practice is to avoid leaving the electrodes in place, because of their tendency to drift over time. This drift may be difficult to estimate. A way to overcome this issue is to prepare self-potential stations with a bentonite plug put in the ground at a depth of about 30 cm. The bentonite plug (obtained by mixing water, salt and bentonite) needs to be capped. A plastic cap would protect the bentonite pot from be washed out by rainwater infiltration (Figure 1.8). This approach can be extremely precise (accuracy on the order of 1 mV or better) for repeating surveys over time.