Estimating groundwater velocity using apparent resistivity tomography: A sandbox experiment

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Abstract. The electrical resistivity tomography (ERT) technique can estimate groundwater velocity to within 5% of the pre-set groundwater velocity. The apparent conductivity obtained by the ERT technique is linearly related to the groundwater conductivity, as described by Archie’s law. Gaussian-like profiles of the tracer concentration were demonstrated with the ERT technique, and the estimated dispersion coefficient was between 0.0015 and 0.0051 cm²/sec. In terms of monitoring changes in groundwater conductivity, the ERT technique has two major advantages over monitoring wells: (1) it measures a larger area and provides more representative results; and, (2) it does not withdraw groundwater samples, and therefore does not affect the groundwater flow. The objective of this research is to measure groundwater velocity with the ERT technique using only one well. The experiments in this research were divided into two parts. The first part evaluated the accuracy and repeatability of the ERT technique using a dipole-dipole array, and the second part estimated the groundwater velocity in a sandbox using the ERT technique. The length, width, and height of the sandbox, which was made of acrylic, were 1.5, 0.5, and 1.0 m, respectively. The ERT sandbox was sequentially filled with 5-cm layers of the silica sand to a total height of 70 cm. A total of 32 electrodes spaced every 5-cm were installed in the center of the sandbox. Three monitoring wells were installed along the line of the electrodes. Both no-flow and constant flow (NaCl solution with electrical conductivity and concentration of 5,000 µs/cm and 2.456 g/L, respectively) tracer experiments were conducted.

1. Introduction

The technique of electrical resistivity tomography (ERT) for estimating the electrical conductivity of soil matrix has two major advantages over traditional methods such as monitoring wells: it is cost-effective and able to measure a large area in a short period of time[1], including mapping of leachate contamination[2, 3], soil remediation[4], and evaluating the moisture content of the soil[5].

The theory of the ERT technique is to apply a current through a soil matrix and measure the induced electrical potential, which depends on the resistivity of the soil matrix and the geometry of the electrodes. A schematic diagram of the electrode arrangement is shown in Figure 1, which depicts the current electrodes (C1 and C2) and the electrical potential electrodes (P1 and P2). The relationship between the applied current, I, and the measured electrical potential difference, ΔV, can be written as equation (1).

\[ \rho_a = K \frac{\Delta V}{I} \]  

(1)

where \( \rho_a \) is the apparent soil resistivity and K is the geometric factor. The geometric factor is a function of the arrangement of the four electrodes (i.e., C1, C2, P1, and P2). Assuming the soil apparent
resistivity to be homogenous, the geometric factor of the electrode arrangement shown in Figure 1 can be written as equation (2).

\[ K = 2\pi \left( \frac{1}{C1P1} - \frac{1}{C1P2} - \frac{1}{C2P1} + \frac{1}{C2P2} \right)^{-1} \]  

The electrode arrangement shown in Figure 1 measures one value of apparent resistivity. The ERT technique installs a series of linearly-aligned electrodes into the surface soil and applies a constant current through two of the electrodes (C electrodes) while measuring the electrical potential between two of the electrodes (P electrodes). The above process is repeated by using different arrangements of C and P electrodes, typically resulting in more than one hundred measurements of \( \rho_a \) in one sequence of measurement. The sequence of measurement is generally called the electrode array. Three of the most used electrode arrays are the Wenner array, the dipole-dipole array, and the pole-pole array. The dipole-dipole array, which is used in this research, places the C electrodes at one side and the P electrodes at the other side such that the distance between the C and P electrodes is larger than 10 times the distance between the C electrodes.

Referring to Figure 2, the sequence of measurements starts with C1 and P1 next to each other and continues as P1 moves away from C1. The distance between the C1 and P1 electrodes determines the depth (i.e., location) of the measured \( \rho_a \). As the P1 electrode moves away from the C1 electrode, the depth increases, resulting in a 2 dimensional (2D) depiction of \( \rho_a \).

The 2D measurement of soil resistivity enables the ERT technique to detect any changes in \( \rho_a \) at depths below the groundwater table without the use of monitoring wells or drilling. Furthermore, because the soil resistivity is a function of the groundwater resistivity, detection of changes in \( \rho_a \) can be used to estimate the changes in groundwater resistivity. When the soil is composed of sand and filled with brine water, the Archie’s law equation can be used to describe the relationship between the soil resistivity, \( \rho_0 \), and brine resistivity, \( \rho_w \), as shown in equation (3)[6].

\[ \rho_0 = F \rho_w \]  

where \( F \) is the formation factor. As the conductivity is the reciprocal of the resistivity, equation (3) can be used to estimate the resistivity of groundwater when the soil resistivity is available. The soil resistivity obtained by the ERT technique can be applied to estimate the groundwater resistivity using equation (3). One application of this technique is to measure the groundwater velocity by conducting a tracer study using brine water with high electrical conductivity as the tracer. The major advantage of this method is that it requires only one injection well, whereas conventional tracer studies require at least one injection and several monitoring wells. In addition, the ERT results represent a spatial distribution of the tracer concentration, whereas a monitoring well provides only a point measurement. Therefore, the groundwater velocity can be estimated using the spatial distribution of the tracer concentration measured at different times. Thus, the objective of this research is to evaluate the ERT technique for measuring groundwater velocity. The other objective is to evaluate the sensitivity of the ERT technique in detecting changes in groundwater conductivity.
Figure 1. Schematic diagram of electrode arrangement for measuring soil resistivity. \( C1 \) and \( C2 \) are the current electrodes; \( P1 \) and \( P2 \) are the potential electrodes.

Figure 2. Schematic diagram showing the relationship between electrode spacing and soil depth during an ERT test. \( C1 \) denotes the electrode where current is applied, whereas \( P1 \) denotes the electrode where potential is measured.

2. Material and methods

The ERT experiments were conducted in a sandbox filled with silica sand saturated with sodium chloride (NaCl) solution. The length, width, and height of the sandbox, which was made of acrylic, were 1.5, 0.5, and 1.0 m, respectively. The diameter of the silica sand ranged between 0.6 and 1.18 mm. A smaller sandbox was constructed to evaluate the relationship between the apparent electrical conductivity and solution electrical conductivity using Ohm’s law. The length, width, and height of the smaller sandbox were 25, 15, and 10 cm, respectively.

The ERT sandbox was sequentially filled with 5-cm layers of silica sand until a total height of 70 cm was reached. After laying down each layer of sand, deionized water (DI) water was added to overflow the sand layer by 1 to 2 cm. This packing procedure was intended to minimize the amount of air bubbles trapped within the sand and maximize the uniform distribution of sand particles of different sizes[7]. The electrodes for the ERT experiments were stainless steel rods with a length of 60 cm and a diameter of 0.6 cm. To ensure that the electrodes behave as point sources/sinks during the ERT experiments, each electrode was insulated along the length with a plastic sleeve so that only a pointed tip of 0.5 cm in length contacted the sand. The layout of the electrodes was centered in the sandbox with 5 cm of distance between adjacent electrodes (Figure 3). As shown in Figure 3, three wells were installed along the line of the electrodes, with well 1 serving as the tracer injection well and wells 2 and 3 serving as monitoring wells. All the electrodes were connected to ERT equipment (McOHM profiler 4XP 32) manufactured by OYO. With a maximum output of 120 mA and 400 V, the McOHM profiler could be connected to 32 electrodes and simultaneously collect 4 sets of current and voltage data. During an ERT experiment, the main output is the apparent resistivity of the soil matrix at different locations.

The sandbox experiments were divided into two parts: accuracy and repeatability characterization, and a tracer study for estimating groundwater velocity. The accuracy and repeatability test was conducted under no-flow conditions. Before each no-flow ERT experiment, NaCl solution with electrical conductivity between 600 and 1,200 S/cm was injected as a plane front from the inlet of the sandbox to purge the DI water until the electrical conductivity of the outflow was the same as the inflow, after which both the inlet and outlet of the sandbox were shut off. The accuracy test was performed by comparing the ERT results to the measured apparent resistivity, which was obtained by first placing the sand and salt water in a small rectangular box and then applying a constant current across the soil matrix and measuring the voltage difference between two adjacent points, and finally using Ohm’s law to calculate the apparent resistivity.
The tracer study was conducted under controlled flow conditions. In a controlled flow experiment, the hydraulic heads on both ends of the sandbox were maintained at a constant level. The electrical conductivity of the inflow solution was first set at 600 S/cm. Once the flow velocity was steady, the solution of 5,000 S/cm was injected at a flow rate of 30 mL/min as a point source 5 cm upstream from the electrode matrix. ERT measurements were then conducted at different time intervals. Three flow velocities were used and compared to the ERT results: 0.25, 0.6, and 0.8 cm/min. During the controlled flow experiments, the resistivity of the solution in both monitoring wells was measured and compared to the ERT results.

![Figure 3. Schematic description of the sandbox ERT experiment.](image)

3. Results and discussion

3.1. Accuracy and repeatability of the ERT technique

The baseline resistivity with which the ERT results were compared is the resistivity obtained from the rectangular box tests. As the conductivity is commonly used to indicate the property of the soil matrix and the soil solution, the resistivity data is converted to conductivity in this section. The relationship between the solution conductivity and the soil conductivity is linear, indicating that Archie’s law (equation 3) is valid for this experiment (Figure 4). The formation factor estimated from Figure 4 is 3.1, which is comparable to values found in literature[6].

The results obtained from the ERT experiments also indicate a linear relationship between the apparent conductivity and solution conductivity (Figure 5), with slopes similar to that of Figure 4. This suggests that the ERT technique can detect changes to solution conductivity. The results from the ERT technique demonstrate the measured apparent conductivity is a spatial function. This is unexpected, as the whole sandbox was carefully prepared and can be assumed to be homogeneous and have uniform conductivity. Therefore, the ERT measurements suggest that the soil matrix in the sandbox is heterogeneous. The degree of non-uniformity can be characterized by the formation factor, which can be calculated with equation (3). The formation factor in the first layer ranges between 3.3 and 5.7 with an average of 4.7, whereas it ranges between 2.4 and 4.2 with an average of 3.3 in the second layer.
Soil conductivity as a function of solution conductivity. 

In addition, the solution conductivity in the monitoring wells was measured and used in equation (3) to evaluate the accuracy of the ERT technique. The results show that the solution conductivities in the three monitoring wells were almost the same, indicating that the solution conductivity in the sandbox was uniformly distributed (Figure 6). It also shows a linear relationship between the solution conductivity and the apparent conductivity. The variation shown in Figure 6 is smaller than that in Figure 5, with the formation factor ranging between 1.4 and 2.5 and an average of 1.2. From the above result, it can be concluded that the formation factor is non-uniform in the sandbox and the change in solution conductivity can be detected by the ERT technique.

The repeatability of the ERT technique was evaluated by measuring the apparent resistivity at 3 different times when the sandbox was filled with a solution of uniform conductivity: initial, 16 h, and 22 h. The results show little changes of apparent resistivity at different measuring times (Figure 7). The coefficients of variation for the data shown in Figure 7 a-c are 4.72%, 3.99%, and 3.75%, respectively. With the coefficients of variation being less than 5% at different measuring times, the repeatability of the ERT technique is acceptable. The ERT experiments were conducted in a sandbox filled with silica sand saturated with saline water.

3.2. Estimation of groundwater velocity

The ERT technique estimates the groundwater velocity by monitoring the changes in apparent resistivity during the tracer study. As shown in the previous section, the apparent resistivity is linearly related to solution conductivity. Therefore, the larger the change in the apparent resistivity is, the larger the solution conductivity is. A typical profile of change in the apparent resistivity is shown in Figure 8. The change in apparent resistivity is calculated by subtracting the background apparent resistivity from the current measurements. It should be noted that each point has a unique background apparent resistivity, which needs to be measured before tracer injection. This characterization of background apparent resistivity is critical for detecting changes during tracer studies. After tracer injection, the plume of the tracer advanced down the gradient as reversed Gaussian-like curves with well-defined maximum changes in apparent resistivity. As the conductivity of the tracer is larger than that of the background solution, the apparent resistivity is expected to decrease as the tracer plume advances. As the plume advances, the spread of the curve increases as a result of dispersion. The shape of the curve suggests that the transport of the tracer follows the advection-dispersion mechanism (Figure 8). The curves shown in Figure 8a were used to estimate the dispersion coefficients in the direction of the groundwater flow. The results range between 0.0015 and 0.0051 cm²/sec with an average of 0.0018 and standard deviation of 0.0015 cm²/sec.
Figure 5. Apparent conductivity from ERT as a function of solution conductivity. (a) 1st layer, depth = 5 cm; (b) 9th layer, depth = 14 cm. x values indicate distance from the left end along the electrode array. Small tank indicates apparent conductivity obtained from rectangular box tests.

The point where the maximum change in apparent resistivity occurred can be considered as the center of the mass of the plume and can be used to estimate the velocity of the plume. As the tracer is inert, the velocity of the plume equals the velocity of the groundwater. To estimate the groundwater velocity, the center of the mass of each plume shown in Figure 8 is plotted as a function of the time after tracer injection (Figure 9). The slope of the curve in Figure 9 is taken as the groundwater velocity. The ERT technique used the first 3 layers of apparent resistivity profiles to estimate the groundwater velocity with %Difference less than 5% (Table 1). This indicates that the ERT technique is able to estimate the velocity of the groundwater by monitoring the advance of the tracer plumes and confirms the feasibility of the main concept of this research.
Figure 6. Apparent conductivity at the locations of monitoring wells as a function of measured solution conductivity.

Table 1. Summary results of groundwater velocity estimation from ERT results.

| Controlled Velocity (cm/min) | Velocity estimated from ERT (cm/min) | % Difference |
|------------------------------|-------------------------------------|--------------|
| 0.25                         | 0.26                                | 4.0          |
| 0.60                         | 0.55                                | 3.3          |
| 0.81                         | 0.86                                | 1.2          |
| 1st layer                    | 0.25                                |              |
| 2nd layer                    | 0.25                                |              |
| 3rd layer                    | 0.27                                |              |
| Average ERT velocity (1st-3rd layers) | 0.26 |              |
|                              | 0.58                                |              |
|                              | 0.73                                |              |

% Difference is calculated using the following equation.

\[ \text{% Difference} = \left( \frac{\text{Controlled velocity} - \text{Average ERT velocity}}{\text{Controlled velocity}} \right) \times 100 \]

3.3. Groundwater conductivity measured by ERT under constant flow conditions

The groundwater resistivity in wells 1 to 3 (Figure 3) during the tracer study with a controlled velocity of 0.8 cm/min was measured in order to monitor the advance of the plume. In the injection well (well 1), the groundwater resistivity and the ERT results had the same pattern: both reached a minimum at 16 min after injection and went back to background values when the tracer plume passed (Figure 10a). The groundwater conductivity in well 2, which was located 30 cm from well 1, had the same pattern as well 1 (Figure 10b). This is unexpected, as the groundwater velocity was only 0.8 cm/min. The reason for this abnormality can be attributed to possible preferential flow paths between the two wells. The ERT results, which reached a minimum value at 65 min after tracer injection, show a more reasonable pattern than the groundwater resistivity (Figure 10b). The above comparison clearly demonstrates one of the main advantages of the ERT technique over monitoring wells: the ERT technique measures the resistivity over a larger area than that of a monitoring well, and hence provides more representative observations than a monitoring well.
The groundwater conductivity in well 3, which is located 60 cm from well 1, has a similar pattern to that of the ERT measurements (Figure 10c). The minimum groundwater resistivity was observed at 66 min after tracer injection, whereas the apparent resistivity from ERT technique reached a minimum at 90 min after tracer injection. This indicates that well 3 was in the path of the groundwater flow and was able to detect the change in groundwater resistivity. The results from the ERT measurements also suggest that changes in groundwater resistivity can be detected by the ERT technique. The reason for the lag between the peaks of groundwater conductivity and ERT measurements can be attributed to the fact that it could take time for the plume to enter the monitoring well. Therefore, to be able to detect real time groundwater resistivity change, forced withdrawal of groundwater sample is necessary.

However, forced withdrawal of groundwater could alter the flow patterns in the vicinity of the monitoring well and cost more time and effort to collect groundwater samples. Therefore, it can be concluded that the ERT technique can detect real time changes in apparent resistivity without disturbing the flow regime and provide a more representative measurement of groundwater resistivity than a monitoring well.

4. Conclusions

The ERT technique is able to detect the changes in apparent resistivity of soil matrix caused by the changes in solution resistivity. The relationship between the apparent conductivity measured with the ERT technique and solution conductivity is linear and can be described with Archie’s law. The formation factors described in Archie’s law are non-uniform within the sandbox. The ERT technique can be used to estimate groundwater velocity with reasonable accuracy and monitor the advance of a conductive plume. The dispersion coefficient of a sandbox can be estimated with the ERT technique. The ERT technique has two major advantages over monitoring wells in detecting changes in groundwater resistivity: results are more representative, and procedures do not disturb the existing flow regime. The ERT has the ability to estimate groundwater velocity with just one injection well.
Figure 7. Apparent resistivity obtained by ERT as a function of distance from the left end of the sandbox at different layers: (a) 1st layer, (b) 5th layer, and (c) 10th layer.

Figure 8. Change of apparent resistivity as a function of distance from the tracer injection point at 3 different controlled groundwater velocities: (a) 0.25, (b) 0.6, and (c) 0.8 cm/min.
Figure 9. Location of maximum change in apparent resistivity as a function of time at 3 different controller groundwater velocities: (a) 0.25, (b) 0.6, and (c) 0.8 cm/min

Figure 10. Apparent resistivity (open square) and groundwater resistivity (open diamond) as a function of time after injection at 3 different wells: (a) well 1, (b) well 2, and (c) well 3.
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