

GEOL 384.3 and GEOL 334.3

Lab #5: Resistivity in modelling tank

In this lab, you will collect resistivity data collected in table-top modeling tank in Rm. 265 Geology (the room where we teach most of our Geophysics classes) and analyse several types of array configurations.

The modeling tank (Figure 1) makes a two-layer model of the subsurface - water of some resistivity and thickness and an infinitely resistive basement (the bottom of the tank). The tank is long but not wide compared to the depth, and so we do not have a truly 1-D model (1-D means a layered structure depending on depth only and infinitely extending in both horizontal directions). In particular, you will see that when the AB distance is large, the sides and end of the tank distort the sounding curve a little.

The city has information on the resistivity of river water and tap water on its website. Tap water resistivity is about 27 Ohm·m and varies a little during the year. The purpose of this lab is to see if we can recover these values from a sounding.



Figure 1. Electrical modeling tank in Geology 265. Note the four electrodes on top in an A-M-N-B configuration for Wenner sounding

To begin the experiments, set up the tank by filling it with water so that the electrodes just reach the water. Before starting the measurements, the resistivity and depth of the water in the tank were measured.

As in lab 4, the resistivity ρ of the medium will be obtained from measured voltage V between a pair of potential electrodes M and N and current I between a pair of current electrodes A and B. The apparent resistivity is calculated by first calculating resistance R and multiplying it by the geometry factor k :

$$\rho_a = Rk, \quad \text{where resistance} \quad R = \frac{V}{I}. \quad (1)$$

The geometry factor is measured in meters and depends on the mutual positions of the electrodes and their spacings.

The SYSCAL resistivity meter (Figure 2) contains a source of current, voltmeter, and a programmable calculator for the values of R and k . During a current injection, the meter measures V and I and reports the values of R and ρ .



Figure 2. SYSCAL Junior resistivity/IP/SP meter used in field schools and labs.

However, reprogramming the meter for every injection takes significant time. Instead of this reprogramming, we will program the meter to always use $k = 1$. This $k = 1$ corresponds to the geometry factor of a Wenner array with spacing $MN = 1/2\pi = 0.1592$ m, and so we used this setting in all our measurements, even those in dipole-dipole and Schlumberger configurations. With $k = 1$, regardless of what array type or spacing we use, the apparent resistivity reported by the meter numerically equals the resistance it measured.

For each of the specific arrays, you will calculate the geometry factors yourself. Multiplying the resistance by the tabulated geometry factor will then give you the apparent resistivity.

Assignments

Wenner array

For a Wenner array the electrodes are configured in a linear sequence A-M-N-B with equal spacings denoted a . The geometry factor for this array is

$$k = 2\pi a. \quad (2)$$

This factor is already calculated in Tables 1 and 2 in the [worksheet file](#).

First, set up the electrodes up in a simple Wenner array with $MN = AB/3 = 0.05$ m.

- 1) **Measure the resistances with injection voltages of 100 V, 50 V, and also smaller voltages** using an additional variable resistor. **Place the results in Table 1.**
- 2) After that, with a 50 V source, measure the resistances again with pulse widths of 0.5 s, 1 s and 2 s. Put the results Table 2 in the [worksheet file](#).

For the remainder of the lab, use pulse widths 1.0 s.

- 3) **Calculate the apparent resistivity values** and write them in the last columns of Tables 1 and 2. As you see from these tables, resistivity should not vary with input voltage or pulse duration by more than about one percent.

You may see some variation with injection voltage, particularly at very low and very high voltages. These variations occur because our electrodes are so small that the current density near them is so large that it physically changes the electrodes during an injection. Note that with such tiny electrodes, current densities are thousands of times larger than they would be in the field.

For the next question, move the A electrode further away (inline) by 1 cm and leave the others fixed. Measure the resistance R again (again, remember that it is reported as “resistivity” by the meter). In the second test in Table 3, move the A electrode back to its original position and increase the separation on MN by 1 cm.

- 4) **Examine the sensitivity of resistivity to errors in the positions of electrodes and fill the empty columns of Table 3.**

For each of the above shifts, **calculate and add in Table 3 values of percent change in the electrode distance AB** (or MN where the potential electrode was moved). For in-line shifts, the shift of electrode is simply added to the respective distance AB or MN, and for cross-line shifts, you will have to use the Pythagoras theorem.

Next, for each array perturbation in Table 3, **calculate the percent changes in apparent resistivity** relative to the original resistivity measured at 50-V voltage in Table 1.

- 5) **Based on the above trials, answer this question:** If you want a Wenner resistivity survey to be repeatable to, say, 5%, how accurately do you need to position the A, B, M, and N electrodes? These are called in-line positioning errors.
- 6) **Repeat** the sensitivity measurements in question 3) by moving the electrodes cross-line by 1 cm (take them out of the holder and hold off the line with insulated tongs. If you try this, make sure the voltage is only 50V and be careful what you touch!). **Put the also in Table 3.**

Question: Are the lateral errors (errors in positioning perpendicular to the line) as important as in-line errors?

- 7) Further in Table 3, **test the effects of resistive elements placed near the array**. Move the electrodes back to their original configuration and measure again, this time holding a resistive element at positions indicated in Table 3. Again, make sure the voltage was only 50V and be careful with what you touch!

The effects of embedded heterogeneity are called lateral effects if the conductor or insulator is near an electrode but off the line of electrodes. If the heterogeneity is inline with the A-M-N-B array, it is the in-line effect.

8) **Looking at the results, answer the following questions:**

- a. Which inhomogeneities are more important for resistivity measurement– those oriented cross-line or in-line?
- b. Which inhomogeneities are more important – those located between M and N, A and M, or outside of the array (A-M-N-B)?
- c. Overall, are cross-line and in-line effects more important at the injection or measuring electrodes?

Sounding using Schlumberger array

A Schlumberger sounding uses a small MN (potential electrode separation) and an expanding AB (current electrode separation). In the sense used here, small MN means that MN is small enough that the apparent resistivity is independent of MN. You can determine this in advance by modeling, but a common rule-of-thumb is that you should have $MN/2 \leq 1/5 AB/2$. However, in practice, $MN/2$ can often be allowed to be considerably larger than this.

Note that when describing electrode arrays, half-spacings are often used ($AB/2$ and $MN/2$) because the half-spacings are conveniently measured from the middle of the array where you usually sit with the recorder. These spacings also give the depths of the corresponding points in pseudo-sections.

The geometry factor for Schlumberger array is

$$k = \pi \frac{AB^2 - MN^2}{4MN} = \frac{\pi}{2} \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{\frac{MN}{2}} \quad (3)$$

where the second formula is useful when using halves of the electrode spacings.

Because of the relatively large distance AB , the apparent resistivity in Schlumberger sounding are almost independent of points M and N, and so the change in apparent resistivity when MN is changed should be small. Changes of apparent resistivity after reconfiguration of the array are called “clutches”. Clutches may also be caused by lateral offsets, such as offsets of electrodes, topography, or cross-line variations of conductivity (metal bodies, fences).

- 9) **Perform Schlumberger sounding using the positions of electrodes listed in Table 4** in the [worksheet file](#). Fill the column of resistances shows the variations of array shape during our Schlumberger sounding in the modeling tank.

Distances $AB/2$ and $MN/2$ are measured from the midpoint of the tank (0.500 m on the tape). Note that AB increases four times before MN increases, and then we increase MN and repeat the reading with the previous positions of A and B. Also notice that there are eight AB increases before AB changes by a factor of ten. Six moves per decade is a minimum, otherwise you will not have enough points to adequately define the shape of the apparent resistivity curve. Eight or ten moves is a maximum for the sake of efficiency. This is about what we do in this lab.

10) **Calculate the missing column of apparent resistivities** in Table 4.

Graph the apparent resistivity vs. $AB/2$ in log-log scale (on log/log paper or by software). How many layers are evident? **Estimate the resistivity of the water** from your sounding curve. This resistivity should be seen from the apparent resistivities at the smallest AB . Does it agree with the known resistivity of the tap water?

11) **Determine the salinity of water in the tank** using the table of salinity vs. resistivity supplied in the preceding lab. Here is that table again:

Table X. Salinity and resistivity of water at 20°C

Salinity (g/l)	Resistivity, ρ_w ($\Omega \cdot m$)
0.07	74.5
0.7	7.8
2.5	2.3
7.0	0.88
70.0	0.11

Sounding using Wenner array

In Wenner sounding, all electrodes are always kept at the equal spacing $MN = a$, and this spacing is increased to perform a sounding. Since all four electrodes are moved each time, the Wenner is more labour intensive in the field than the Schlumberger. The geometry factor for Wenner array is given in eq. (2), and it is calculated for our sounding experiment in Table 5 in the [worksheet file](#).

12) **Perform Wenner sounding and write resistance results into Table 5.**

13) **Calculate the column of apparent resistivities** in Table 5. **Plot these apparent resistivities** as for Schlumberger array sounding.

You will see that the apparent resistivities for Wenner array are not the same, despite the fact that the tank is exactly the same. The reason for this is that apparent resistivities are a function of the geometry of the array as well as the actual resistivities in the ground. However, rigorous inversion of these two soundings would give fairly similar models.

Sounding using a dipole-dipole array

- 14) **Next**, set the equipment and **perform a dipole-dipole sounding profile** through the tank, with a conductive or resistive target in the middle. Record the results in Table 6 in the [worksheet file](#).

In a dipole-dipole array, the electrodes are arranged in sequence A-B-M-N, with *AB* and *MN* spacings relatively small and equal, and *MN* being moved away from *AB* in steps equal to the *AB* spacing. The geometry factor is

$$k = \pi MN \cdot n(n+1)(n+2), \quad (2)$$

where $n = BM/MN$ is the number of *MN* spacings between the lead current electrode (B) and the trailing potential electrode (M).

Table 6 also contains another geometry factor k' which has been computed by Prof. Sam Butler using modeling software (Comsol) to allow for the restricted geometry of the tank. If you use this number, the apparent resistivities will look like if the tank had infinite dimensions.

- 15) **Calculate the column of apparent resistivities** in Table 6.

Pseudo-section

A pseudo section is a color or contour map of apparent resistivity vs. “pseudo-depth” and “pseudo-position”. The goal of selecting these pseudo-coordinates is to make the pseudo-section looking generally close to the true resistivity section in a simple layered structure (i.e., the different levels of resistivity shown at close horizontal positions and reasonable depths). For symmetric arrays, the horizontal position (called pseudo-position) is the middle of the array. For dipole-dipole arrays, the pseudo-position is taken at the middle of segment B-N (middle of the whole four-electrode arrangement).

To define the pseudo-depth, note that when you collect an apparent resistivity with a given electrode spread, half of the current flows between the surface and the midpoint of the array. Since the horizontal size of this current is $AB/2$, the ‘averaging center’ (vertical size of the fan of current streamlines) might also be something like $depth = AB/2$. This half-distance between current electrodes is taken as the pseudo-depth for Wenner array.

For a double dipole (dipole-dipole) array, the pseudo-position and pseudo-depth are determined from the positions of the centres of the current- and potential-electrode arrays: $x_c = (x_A + x_B)/2$ and $x_p = (x_M + x_N)/2$. The pseudo-position is then $x = (x_c + x_p)/2$ and pseudo-depth $z = |x_p - x_c|/2$. For a perfectly symmetric array as in our lab, these formulas simplify to $x = (x_A + x_N)/2 = (x_B + x_M)/2$ and $z = |x_M - x_A|/2$.

- 16) **Calculate in Table 6** columns of pseudo-positions of the array and pseudo-depths. **Plot** and contour a pseudo section for dipole-dipole sounding above by software (Matlab/Octave).

To illustrate how the resulting pseudo-sections could look like, Figure 3 (next page) shows a simple drawing of the numerical values and a color plot from Matlab. When using the first of these formats,

you will need to also draw in several contours of apparent resistivity by hand.

Try recognizing the resistive and conductive elements inserted in the tank.

Hand in:

Brief answers to the questions highlighted in **bold** above with figures embedded in a Word or PowerPoint document by email.

DIPOLE DIPOLE IN TANK

9.1 **.30.5** **31.9** **38.8** **63.9** **42.8** **29.6** **29.3** **30.2** **30.8** **10.3** **31.3** **32.8** **31.2** **32.0** **27.9** **30.7**

.34.0 **29.8** **12.6** **51.2** **49.7** **40.0** **28.6** **27.7** **28.6** **28.6** **31.9** **31.9** **28.9** **29.2** **27.7** **26.2**

.81.3 **31.6** **38.4** **30.9** **35.4** **33.1** **24.8** **23.3** **23.3** **23.3** **26.4** **23.3** **23.3** **23.3** **21.8**

.22.2 **28.7** **19.6** **18.1** **24.2** **24.2** **19.6** **16.6** **18.1** **19.6** **18.1** **16.6** **16.6** **15.3**

.19.5 **12.7** **10.8** **11.6** **16.4** **16.9** **14.5** **12.4** **11.6** **10.6** **10.8** **10.3** **8.2**

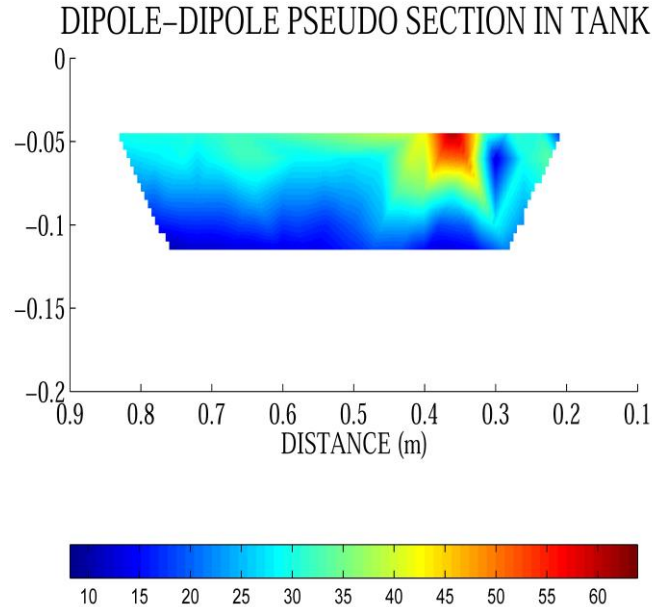


Figure 3. Examples of expected pseudo-section displays (in the first one, you are should also draw in contours of constant values of apparent resistivity).

Additional material (for information only; no assignments in this section)

Observation of resistive and conducting targets by sounding in modeling tank (by Jim Merriam, with additional comments by I.M.)

In general, conductive targets are more easily detected than resistive targets of the same size and at the same depth. That is, if you had a conductive target (say 100 times as conductive as the host rock) and a resistive target (a 100 times more resistive than the host) of the same dimensions and depth below the surface, the conductive target would produce a greater anomaly in apparent resistivity. Figure 4 shows a gradient mode (pole-dipole array) prediction for apparent resistivities in the modelling tank response of a conductive target (1000 times more conductive than the water, blue dots) and a resistive target (1000 times more resistive than the water; red dots). In both cases, the target is a cylinder of 1.5 cm in diameter and 12 cm long. The top of the target is located at 2 cm below the surface.

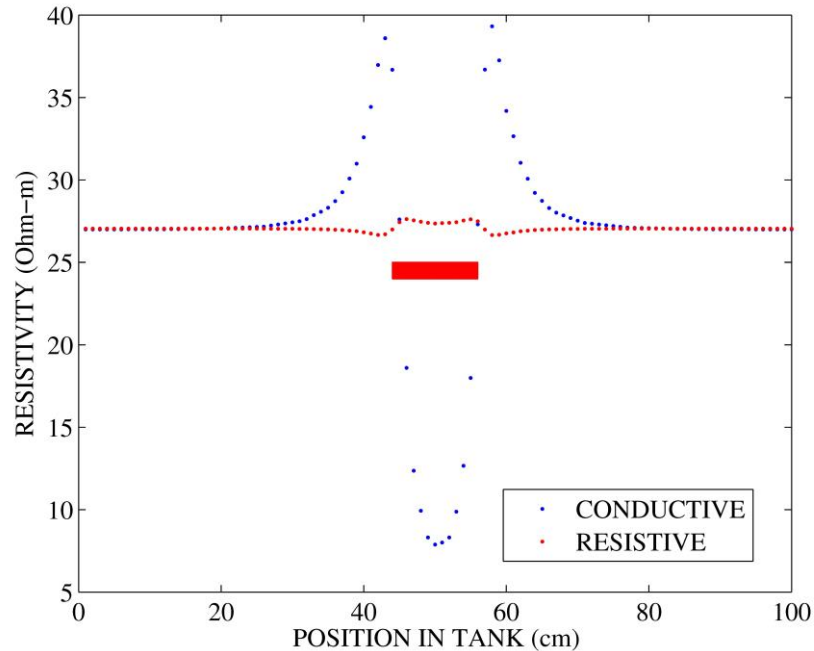


Figure 4. Numerically modeled apparent-resistivity profile obtained by a pole-dipole array in the modeling tank. At the center of the tank, a conductive or resistive cylinder (red) is placed at in the water (red rectangle). The corresponding apparent resistivities are shown by blue dots and red dots, respectively.

A dipole-dipole pseudo section would look different, but the apparent resistivities should be in the same range.

In Figure 4, note that the apparent resistivity in the resistive case is only one percent higher than the resistivity of the water. This is despite the 100-times difference in the actual resistivity. In a field situation, we often only get repeatability (measurement error) of five percent, and therefore small resistive targets like this might not be detectable. In the conductive case (blue dots), the apparent resistivity at the middle of the target is almost five times less than the resistivity of the water (yet also not 100 times as the true resistivity of the target).

Note that there are sidelobes of the apparent resistivity at both ends of the cylinder. These increases of apparent resistivity are opposite in effect to what you might expect. That is, near its ends but outside of it, the conductive cylinder shows apparent resistivities greater than the resistivity of the water (blue dots), and the resistive cylinder shows apparent resistivities less than the resistivity of the water (red dots). This counter-intuitive effect is only seen in 3-D geometry and arises from the secondary charges and current flows near the target.

The pattern of the apparent resistivities at the ends of the target can be understood as follows. First, note that the apparent resistivity is calculated from the measured resistance $R = \Delta V/I$, which means that the plots in Figure 4 actually represent the gradient of the potential φ : $V \propto \partial\varphi/\partial x$. From these plots, the potential itself, $\varphi(x)$, would look like a positive peak over the left end of the cylinder and a negative peak over its right end. These peaks of the electric potential are produced by charges induced on the ends of the conductive or resistive cylinder. If the cylinder is conductive, the induced charges are large and such that they nearly

compensate the external field, so that is the end of the cylinder located farther away from the source is charged positively. If the target is resistive, the induced charges are smaller and may be directed oppositely in the 3-D case.

Figure 5 shows a Schlumberger array response to a 1-m thick layer at 20 m below the surface. In one case, the layer is resistive (resistivity is 1000 times the host-rock resistivity, solid line), and in the second case the layer is conductive (1000 times less than the host resistivity). The host rock resistivity is 50 Ohm-m.

As you can see, for a boundless layer, the difference between the resistive and conductive cases is not so extreme as in Figure 4. The apparent resistivity in the resistive case is about five times the host resistivity, and in the conductive case, the apparent resistivity is about 10 times below the host resistivity. Thus, the sensitivity of imaging is again higher for conductive targets than for resistive targets.

Note that in 1-D geometry, the apparent resistivity is always bracketed by the highest and lowest actual resistivities. However, the actual resistivity levels are also far from being reached by the apparent resistivity. This is because the layer is thin, and significant currents bypass it. In particular, current tends to avoid resistive bodies.

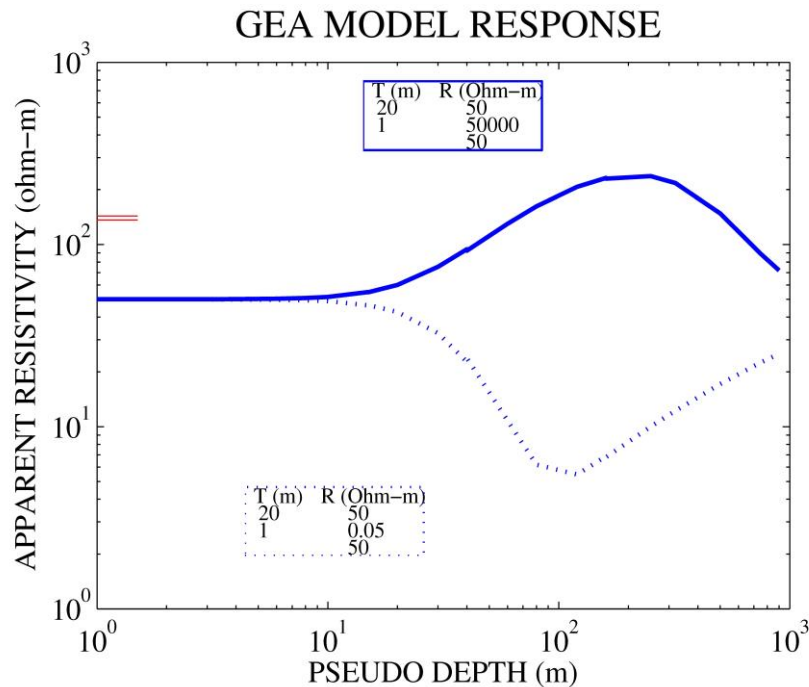


Figure 5. Modeled pseudo-section of numerically modeled responses of a conductive (blue dots) and resistive (red dots) cylinder (red) placed at the center of the modeling tank (red rectangle).