N-LAYER
Soil Resistivity Measurement Analysis Computer Program

REFERENCE MANUAL

Ground-it.com Consulting Ltd.
4030 Felix Court
North Vancouver, B.C.
Canada, V7G 2P3
Telephone: 604 986 7890   Facsimile: 604 929 5630

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1. OVERVIEW

N-Layer is a soil resistivity measurement analysis computer program.

N-Layer will attempt to fit a perfect horizontally layered soil structure to a set of soil resistivity measurements that were carried out using the "Wenner" method - see Figure 1.
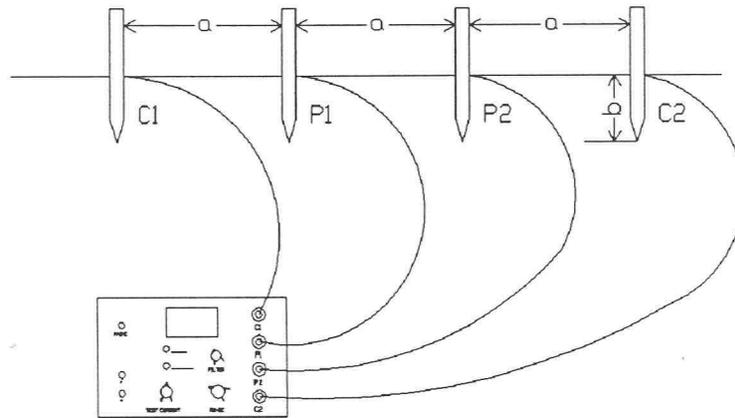
Figure 1 "Wenner" Soil Resistivity Test Method

The "Wenner" method is described in [1]. It is one of the most widely used methods for measuring soil resistivity for electrical grounding purposes. In carrying out the measurement, four test rods are inserted a short distance into the soil in a straight line with equal spacing between the probes. A test current is applied to the outer probes and the resulting potential difference between the inner probes, is measured. The potential difference divided by the test current give an apparent resistance in ohms. The apparent soil resistivity is obtained from the measured resistance.

For test configurations where the test probe depth is small compared with the probe spacing so that the test probes appear approximately as point sources, the apparent resistivity is given by the following equation:

$$\rho = 2\pi a R$$

where: ρ is the soil resistivity
a is the probe spacing
R is the measured resistance

ρ is an apparent resistivity for that particular test probe spacing. In most instances a series of measurements will be taken using different probe spacings. When the apparent resistivity is plotted against the probe spacing, it is often found to vary considerably as the spacing is changed. This is due to non-uniformity of the soil. In reality, the structure of soil may be very complex with vertical and/or horizontal layers and/or pockets of soil having differing resistivities.

N-Layer will attempt to derive a perfect horizontally layered resistivity structure that would produce "Wenner" measurement results that match the field data as closely as possible.

Two methods are used. Both require the user to enter an estimated soil structure as a starting point:

1.1 2-Layer Method

This is based on Appendix B of [1]. (It should be noted that the equations in Appendix B of [1] have some typographical errors that are corrected in the program)

The 2-Layer method uses curve fitting to achieve the best fit. Only 2-layered soil structures can be derived using the 2-Layer method.

1.2 N-Layer Method

The N-Layer method use a filter function method to develop the best fit soil structure. It is based on [2]. The N-Layer method can derive a soil structure of from 2 to 10 layers, from appropriate input data.

1.3 Software Changes Since Previous Revision

The previous revision of the manual was dated April 05, 2001.

The operation of the N-Layer method has been changed. The user should read Section 3.2. The way the program generates input data with probe spacing in logarithmic increments, has been changed. Use of the N-Layer method places certain restraints on the format of the input data.

The field data can now be entered in any order. The program will automatically sort it into order of increasing probe spacing.

The name of the main program file has been changed to N-Layer.exe. Previously it was Nlay2.exe.

2. DOING CALCULATIONS

The security key supplied with the program, must be attached to the computer parallel printer port to enable the program to run.

N-Layer is a standard windows 95/NT program. It can be started by double clicking on the icon for the program. The user can also drag an N-Layer data file from the File Manager onto the program icon and it will be immediately loaded. Although N-Layer files are text files, they should have the extension **.nly**.

Data files can be created within the program by entering the measurement results. The following field measurements are used to illustrate this. The first column contains the test probe spacing in

metres, the second the test probe depth in metres and the last, the measured apparent resistance in Ω:

```
 1.000        0.100        67.0
 2.000        0.100        25.6
 4.000        0.100        10.27
 6.000        0.100         4.38
 8.000        0.100         2.87
12.000        0.100         1.629
16.000        0.100         1.225
20.000        0.100         0.990
24.000        0.100         0.831
30.000        0.100         0.700
36.000        0.100         0.584
```

Run the program by double clicking on the desktop icon or the program file name **N-Layer.exe** in the Windows Explorer. A blank window with the usual Windows menu selections appears.

Select **Edit** from the menu and a dialogue box will appear into which the above data can be entered. Some default entries appear in the dialogue box. The **Traverse** defaults to **1**. Anything can be entered to describe it. **Date** defaults today's date. Suitable text can be typed into Description and Equipment. None of these entries has any effect on the calculation results, but the **Traverse** number and **Date** will appear at the top of graphical plots.

Go to the table headed **Soil Resistivity Measurement Data**. Type in the above data. Note that when the program runs, it will read data from row 1 until there is a blank row. There are enough rows in the table for 100 measurement results. The data can be entered in any order. The program will sort it into order of increasing probe spacing.

Now enter the layer resistivity and height guess. This requires some experience, but good starting values can often be obtained by selecting the **OK** button at this point and noting the shape of the plotted results. It will be seen the plot starts at about 420 Ω-metres at 1 metre probe spacing and the resistivity decreases to about 120 Ω-metres at 36 metres spacing. The 4 metre point on the curve is approximately mid-way between the 1 metre point and where the curve flattens out. As a start, use these values for a soil guess.

Select the **Edit** menu option again and enter **4** for the layer 1 height in the table headed **Height and Resistivity Guess**. Enter **420** as the resistivity guess for this layer. A 2-layer fit will be tried the first time. It is therefore only necessary to enter the resistivity of layer 2 as **120**. The height of layer 2 has no effect as layer 2 will extend to infinity depth.

In the **Select Program** group, click the 2-Layer radio button to use the two-layer algorithms. As the two layer process requires more iterations to converge on the data than the N-Layer, set **Iterations** to **500** and click OK.

Now select the **Calculate** menu option. You should see a progress bar as the calculation proceeds and then the calculated curve will be plotted on top of the measurement curve. The curves are marked **Meas**. and **Calc.** The soil model is given at the top of the plot as a first layer with height 2.162 metres and resistivity of 413.571 Ω-metres and a deep layer resistivity of 122.974 Ω-metres.

At this point, save the data to a file using the usual **File|Save As** menu selection and choose the samples sub-directory and the file name **Trav1**. You can now use the Windows Notepad program to read the data file, which will look like the following:

```
TRAVERSE
1
DATE
August 11, 1998
DESCRIPTION
Enter a description of the measurement
EQUIPMENT
DET-2 Digital Earth Tester
METHOD
2-Layer
NUMBER OF LAYERS
2
HEIGHT GUESS
      4.000
RESISTIVITY GUESS
   420.000    120.000
ITERATIONS
500
ACCURACY
0.00100000
NUMBER OF READINGS
11
FIELD DATA
     1.000       0.100       67.00000
     2.000       0.100       25.60000
     4.000       0.100       10.27000
     6.000       0.100        4.38000
     8.000       0.100        2.87000
    12.000       0.100        1.62900
    16.000       0.100        1.22500
    20.000       0.100        0.99000
    24.000       0.100        0.83100
    30.000       0.100        0.70000
    36.000       0.100        0.58400
END
```

Click on the **Tools** menu and to **Export Results to Text File**. This will create a text output file with the same name and extension **.out** - **Trav1.out**. The results file will look like the following:

```
 Input File:
```

```
   Traverse: 1
        Date: August 11, 1998
Description: Enter a description of the measurement
  Equipment: DET-2 Digital Earth Tester


2-LAYER CURVE FIT
(Based on the method described in Appendix B of IEEE Guide 81 - 1983)
Upper layer resistivity estimated value:    420.0
                                 Deep layer:   120.0
         Estimated depth of upper layer:      4.000
     Initial increment factor step size:      0.005000
   Maximum number of terms to calculate: 500


11 Measurement points
    1    1.0    0.10     67.000      423.4
    2    2.0    0.10     25.600      322.2
    3    4.0    0.10     10.270      258.2
    4    6.0    0.10      4.380      165.1
    5    8.0    0.10      2.870      144.3
    6   12.0    0.10      1.629      122.8
    7   16.0    0.10      1.225      123.2
    8   20.0    0.10      0.990      124.4
    9   24.0    0.10      0.831      125.3
   10   30.0    0.10      0.700      131.9
   11   36.0    0.10      0.584      132.1


Best fit obtained on iteration No. 435
Upper layer resistivity:       413.57
            Deep layer:        122.97
   Upper layer thickness:        2.16


Comparison below is based on these calculated values:


Spacing    Meas R      Calc R       Error
   m       ohm-m       ohm-m          %


   1.0     423.4      400.7          5.4
   2.0     322.2      348.0         -8.0
   4.0     258.2      231.4         10.4
   6.0     165.1      171.5         -3.8
   8.0     144.3      146.6         -1.6
  12.0     122.8      131.1         -6.8
  16.0     123.2      127.0         -3.2
  20.0     124.4      125.4         -0.8
  24.0     125.3      124.6          0.5
  30.0     131.9      124.0          6.0
  36.0     132.1      123.7          6.4


               RMS Error      5.7%
```

There is quite good agreement between the curves. The "calculated" curve is the curve that would be obtained if the soil had the perfect layered structure interpreted from the measurements. An even better fit can be obtained using a 3-layer curve fit as follows:

Go to the **Edit** dialogue box.

Select the **N-Layer** radio button and enter 3 as the **Number of Layers**.

Leave the layer 1 height at 4 metres and set the layer 2 height to 4 metres.

Set the layer resistivities for layers 1, 2 and 3 to 450, 120 and 130 respectively and press **OK**. The above changes are in file **Soil13.nly**.

Select to **Calculate**. A warning message will state that there are too many iterations for the N-Layer method and the number of iterations is being set to 10. A better curve fit should be obtained.

The soil structure is now:

Layer	Height	Resistivity
1	2.277	422.247
2	23.731	115.394
3	∞	167.500

Colour plots of the curve fits are attached.

3. PROGRAM NOTES & LIMITATIONS

The edit dialogue box contains a check box marked Detailed Output and another marked Accuracy.

Detailed Output will produce a detailed listing of the convergence of the analysis for both the N-Layer and 2-Layer algorithms. For the N-Layer algorithm, each step of the data fit is listed in summarized form and one can see how the program converges to a solution. For the 2-Layer curve fit, each step is also listed. The listing can be much longer because more iterations are needed.

Accuracy should normally be left as 0.001. It only affects the N-Layer algorithm and can be used to stop the data fit when it is sufficiently close that the error is negligible.

3.1 Allowance for Probe Depth

The 2-Layer process described in [1] is for measurements taken with point source probes. Usually the probes penetrate a few cm into the soil and there would be some error in the resistivity when the probes are close together.

In this program, equations described in [2] are used to calculate the resistivity for each probe spacing. This may not be strictly correct as the curve fit assumes the measurements were taken at the soil surface.

The same approximation is applied for the N-Layer algorithm.

3.2 Modification of Data When Using N-Layer

The N-Layer process requires logarithmically spaced measurement data. Often this is not available. The program will develop logarithmically spaced data from the data provided by the user. It will develop a new data set with probe spacings that have 6 logarithmic increments per decade. The maximum spacing will be equal to the maximum spacing input and the minimum spacing will be less than or equal to the smallest spacing input.

For best results, the measurements should be done approximately logarithmically with about 6 increments per decade.

Starting with 1.0 metre as the narrowest probe spacing, a suitable set of logarithmic probe spacings (rounded to 1 decimal place in metres) is:

> 1.0, 1.5, 2.2, 3.3, 4.6, 6.8, 10.0, 14.7, 21.5, 31.6, 46.4………….

If the starting spacing is 0.5 metres:

> 0.5, 0.7, 1.1, 1.6, 2.3, 3.4, 5.0, 7.3, 10.8, 15.8, 23.2, 34.1, 50.0………….

The spacings could be rounded to the nearest metre for spacings greater than 2 metres. The following sequence of probe spacings should provide good measurement data:

> 1, 1.5, 2, 3, 4, 6, 8, 12, 16, 24, 32, 48……….

When the last spacing set is used with the centre of the traverse fixed, for many spacings, the potential probes can be inserted in the same holes that were created by the current probes.

Other test arrangements are possible. One method used, keeps the P1 probe at the same location and moves the C1, P2 and C2. This effectively moves the centre of the traverse, which could improve averaging over an area.

Previous versions of the program used the narrowest probe spacing as the starting point for the logarithmic data, which is based on interpolation from a spline curve fit of the input data. The effect of this was that often, the widest spacing measurement results are lost. For example, if data with probe spacings of 1 to 36 as used, the output would cover from 1 to 31.6 metres.

The program has been changed to generate new data using the widest probe spacing as the last point in the new data set. It will generate spacings starting equal to or less than the smallest spacing in the input data, up to the widest spacing. Using the same example of 1 to 36 metres input data, the output will now be from 0.776 to 36 metres. The spline curve fitting algorithm will usually fit the data quite well.

Because the new data will always have 6 increments per decade, the final number of points can be less, equal to or more than the original number of points.

3.3 Impossible Results

There is virtually no control over the input data for the program. The user can provide any data values. Actual measurement results will cover a wide range of values. As a result, the program may sometimes produce "impossible" curve fit results.

Examples of "impossible" results are:

Deep layer resistivity is very low 0.01 Ω-metres or very high 100000.0 Ω-metres.

Layer thickness is very small, for example 0.001 metres. This is usually combined with very low or very high resistivity for the thin layer.

Even if the data was obtained from actual field test results, it is possible that these effects will be obtained. There are a number of reasons:

- The soil resistivity may not be horizontally layered. There may be a pocket of soil with a different resistivity, or the soil may be vertically layered.

- The user may be trying to fit too many layers to the data. For example, if a two layer fit is quite good, trying to do a three layer fit may result in a very thin layer with nearly zero or very high resistivity because the algorithms try to make a more perfect fit to data that may have some small irregularities.

- The test instrument may be susceptible to error when the probe spacing is too wide. Most instruments will suffer from some inductive coupling between the test leads when measuring very low values of resistance. This even applies for instruments that claim to use "switched dc". The effect can be tested if partly wound test lead spools are used, by arranging the spools with the axis aligned and at right angles. If the readings change, there are errors due to test lead coupling.

A particularly difficult interpretation occurs when the top layer resistivity is low and the deeper layers are high as may happen when there is a layer of conductive soil on top of rock. One can appreciate why this is difficult to measure when one realizes that information about the deep layer must be obtained by passing a current and measuring a voltage through the conductive layer. Very little of the signal will reach the deep layer and any small irregularities in the uniformity of the soil may lead to large differences in the interpreted deep layer resistivity.

4. REFERENCES

1. "IEEE Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Ground System", IEEE Std. 81-1983.

2. P.A. Davis, "Development and Application of Resistivity Sounding Inversion for Several Field Arrays", Thesis submitted to the Faculty of the Graduate School of the University of Minnesota, August, 1979.