

Cross Borehole Electrical Resistivity Tomography (ERT) Measurements

Introduction

Resistivity imaging at the surface may be used for applications such as cavity detection, geotechnical investigation, site characterization, monitoring of groundwater recharge, detection of LNAPLs and DNAPLs. Resistivity imaging produces images, showing the resistivity distribution in the ground. Resistivity variations can then be related to geology, subsurface moisture content, porosity, temperature, and pore fluid chemistry.

Why put electrodes in boreholes?

The resolution of surface resistivity imaging decreases with depth. Cross borehole Electrical Resistivity Tomography (ERT) provides a more uniform model resolution vertically. Geotechnical, environmental and remediation projects often require detailed information about contaminant migration at depth.

Sometimes there is no place for surface electrodes, for example the ground below a bridge foundation or under a building may need to be investigated. Two or more holes can be drilled on either side of the structure and measurements can then be performed under the object.

2D – 3D

The goal of 2D ERT is to produce a resistivity image on a plane most commonly vertical. Mixed surface and borehole electrodes may be used for better resolution as long as all electrodes are in the same plane. Inversion of a 2D data set takes from a few seconds to several minutes.

3D ERT shows volumetric resistivity distribution between all electrodes. The electrodes are usually installed in three or more boreholes and on the surface. Inversion of a 3D data set may take from several minutes to several days depending on the number of data and electrodes.

Survey design

The geometry of the set-up is important. The boreholes should not be too far apart. The relationship between the borehole depth and distance between two boreholes is called **aspect ratio**. The aspect ratio should be equal to or greater than 1.5

For a 2D survey the boreholes and the surface electrodes should all be placed in one plane.

For a 3D survey there needs to be a minimum of three wells. Four boreholes with data collected along six 2D transects (AB, AC, AD, BC, BD, and CD) make

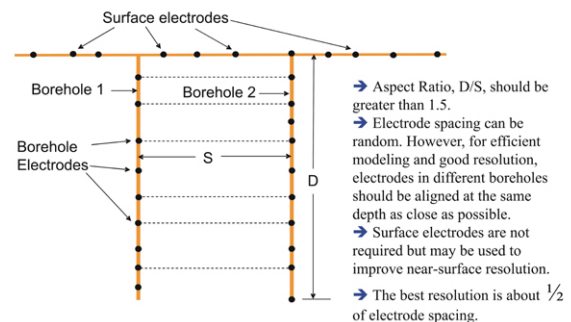


Figure 1 Aspect ratio and electrode spacing are important parameters for a successful survey.

a perfect 3D data set. The rectangular size of ABCD (see Figure 2) can be increased by adding a fifth borehole in the middle. This way the investigated volume can be increased.

The electrodes should not be placed too far apart in the borehole or on the surface between the boreholes. Typically you can not see targets smaller than half the electrode spacing. Note that this rule of the thumb is just valid for the area near the electrodes, further away the target has to be larger in order to be detected. Therefore if you are looking for cavities of 1 meter diameter, you should not use electrode spacing larger than two meters.

During the final processing the AGI EarthImager inversion software creates a mesh based on the location of the electrodes. In order for the EarthImager to create an effective mesh, i.e. a time saving mesh, the electrodes need to be installed at the same level in the two bore holes. If for example the electrodes are installed with 1 meter spacing, the electrodes in both holes should be at the same level, for example -1, -2, -3, etc. meter in both boreholes and not -1, -2, -3,.... in one bore hole and -1.5, -2.5, -3.5,..... in the other (see Figure 1.). In the later case the mesh will double in size and the processing time will increase drastically.

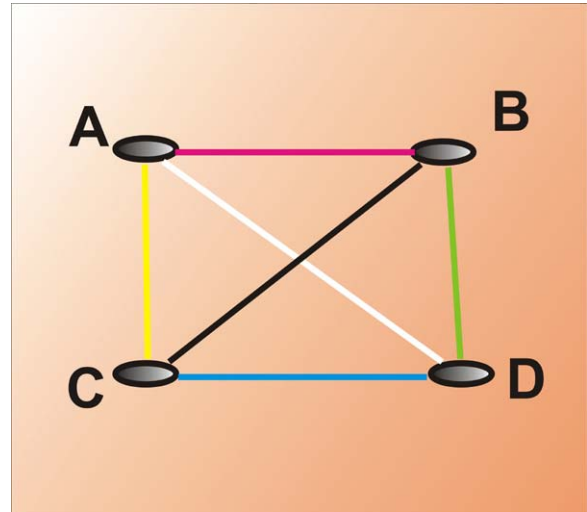


Figure 2 Measure all six transects AB, AC, AD, BC, BD, and CD.

Command files

Before the survey can start, a command file needs to be loaded into the SuperSting RAM memory. The command file controls how the measurement is performed, i.e. tells the resistivity meter how to collect the data. A suitable command file can be created by the EarthImager software. See Command creator in the EarthImager instruction manual.

There are currently two types of command files available from the EarthImager; a dipole-dipole command file and a bipole-bipole command file. Once the creation of the command files is finished, an animation can be run in the EarthImager in order to inspect the measurement scheme closely. When the command file is OK, it is loaded into the SuperSting RAM memory using the Administrator software.

The dipole-dipole electrode array will give the highest resolution, however the bipole-bipole gives the strongest signal to measure. Therefore it would be best to use the dipole-dipole command files in order

Dipole-dipole array with SuperSting 8-channel instrument

Inject electric current from one pair of electrodes, and measure potential differences with 8 receivers simultaneously.

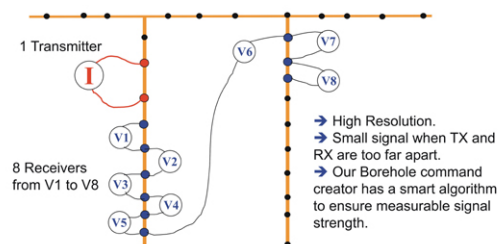


Figure 3 Dipole-dipole gives the highest resolution but low signal strength.

to get the highest resolution, but in areas of low resistivity it may not be possible to measure and fit data from a dipole-dipole survey properly.

The EarthImager command creator has a smart algorithm to ensure measurable signal strength, however in low resistivity areas this may result in too few measurable points. Therefore at sites where the resistivity is lower than 100 Ω meter, use the bipole-bipole command file, at sites with larger resistivity use the dipole-dipole command file. Best is of course to measure with both files and invert them together in the EarthImager, but that would approximately double the field survey time and increase the processing time.

To create a command file for 3D ERT, one must have the electrode coordinates in a single coordinate system. Set the surface $z=0$ and negative z downward.

Type of electrodes

There are different types of electrodes and electrode cables for borehole surveys available from AGI. The dual mode smart electrodes used on land are not suitable to put in a borehole. Instead, passive cables with electrodes molded on the cable at user specified intervals are used together with a Switch box on the surface. Note that passive and active (dual mode) cables can be mixed so that dual mode electrodes are used at the surface and passive cables and electrodes are used in the borehole.

From AGI a special borehole cable with a 1,500 lb strength member and water block is available with electrodes molded onto the cable. The water block is a polymer which prevents water from getting into the cable in case of a cut in the outer jacket.

The passive borehole electrode comes in two types; stainless steel or graphite (patent pending). When an electrical current is passed through a stainless steel electrode, which is in contact with water, the electrode will corrode because of electrolysis. This process is fairly rapid and will severely deteriorate the electrode if it is buried in the ground for long periods of time for resistivity monitoring applications.

Bipole-bipole array with SuperSting 8-channel instrument

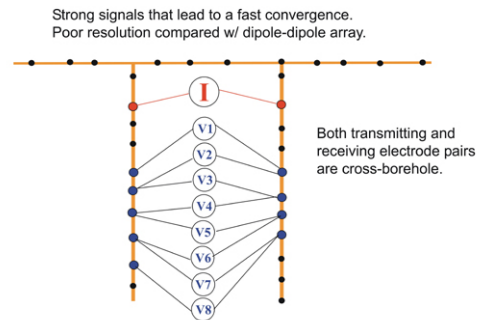


Figure 4 Bipole-bipole gives a strong signal but less resolution than the dipole-dipole array.



Figure 5 Graphite electrode.

The advantage of the graphite electrode is that it does not corrode because of electrolysis. The price of the graphite electrode however is approximately 35% more expensive than the stainless steel electrodes.

If the passive cables are used in water filled holes, it is easy to pull the electrodes up and clean off the corrosion, using for example a brillo pad, if the corrosion is not too severe.

The diameter of both the stainless and the graphite electrodes are 1.0", the length of the active surface is 1.25".

For a 2D or 3D cross borehole survey you will need:

- At least 2 installed borehole cables and maybe some surface electrodes. For 2D survey it is possible to use one borehole and surface electrodes.
- SuperSting R8/IP is the best choice, however SuperSting R1/IP is sufficient, but the survey will take much longer, with 50 electrodes in two boreholes, one may collect about 1,000 data points.
- A Switch box for the borehole cables to connect to.
- Standard cables to connect to PC, battery, and Switch box.
- One or two deep cycle 12 V batteries.
- The EarthImager software, 2D or 3D version depending on type of survey.

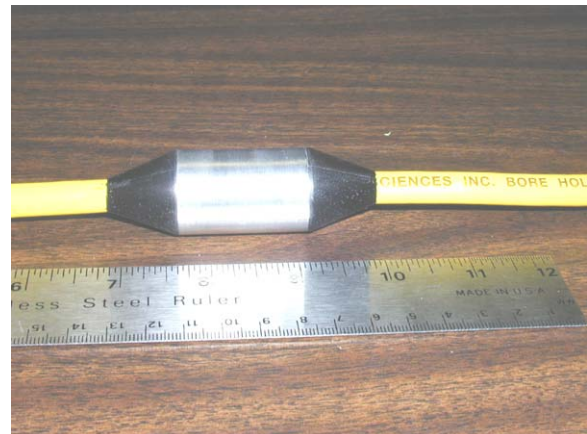


Figure 6 Stainless steel electrode.

Electrode installation

It is important that the electrodes are installed in full contact with the soils or rocks, so that transmitting electrodes can inject an electric current into the ground and potential electrodes can sense the electric field. Contact to the formation is provided by water in the hole. In case of dry hole some other media like mud, concrete grout or sand may be used to establish connection between formation and borehole electrodes. Depending on the geological situation there are different ways of installing the electrodes.

Metal casing in a borehole would short-circuit electrodes resulting in noisy data and may cause damages to the instrument. Note that electrodes can not be installed outside or inside metal casing in the hole, since the metal casing would short-circuit all electrodes even if the electrodes are installed outside the metal casing. The electrodes can not be installed inside a PVC (plastic) casing, since the PVC would insulate the electrodes from the ground.

Electrode cables may be permanently installed in the ground with cement grout for long term monitoring applications. To install a retrievable borehole cable, bentonite grout or something similar

should be used. For best result, it is important to match the resistivity of the grout to the resistivity of the formation. Try to use a grout with resistivity similar to the formation resistivity. If the grout material is too conductive, current channeling along the borehole would deteriorate the resolution of the resistivity image.

Bentonite grout has very low resistivity, approximately 5 Ω meter and is therefore mainly useful in clay rich environment or at polluted sites. Regular cement has a higher resistivity, say 100-200 Ω meter making it suitable for use in areas of higher resistivity. In other areas a mixture of sand and local ground water may be the best choice.

At sites where the ground water is close to the surface, or where the hole will hold water, the electrodes can be installed simply hanging in the cable down the borehole. The connection between electrode and formation is provided by the water. If there is a risk of collapse the hole can be cased with slotted PVC casing. The casing needs to be slotted all the way to permit the connection between the electrodes and the formation. However, slotted PVC can only be used where there is water in the hole to make the connection between the electrode and the formation.

Open, water filled borehole

In case of open, water filled holes, it is simple, just hang our passive borehole cables in the borehole, maybe with a weight attached at the bottom end to keep the cable straight. Steel casing, often occurring at the top of the hole, will affect the measurements negatively. No electrodes can be used within the steel casing and electrodes close to the steel casing at the top part of the hole may not be possible to use.

Cased water filled borehole

Neither steel nor PVC casing can be used when performing electrical resistivity measurement. The steel will short circuit the electrodes and the PVC will electrically isolate them from the formation.

Therefore, if the hole needs to be cased, use slotted PVC casing all the way. The passive cable and electrodes are then simply hung inside the slotted PVC casing. The water will provide the contact between the electrode and the formation through the slots in the casing.



Figure 7 Slotted PVC screen. A cloth sock can be used in case small particles need to be prevented from entering the well.

Open hole in the vadose zone



Figure 8 Surveying between two boreholes. Using surface electrodes improves the resolution near the surface.

Use bentonite mud, grout, or wet sand to set the passive cable and electrodes in the hole. The material makes the contact to the formation. If a mud is used, it may be possible to retrieve the cable for use in another hole. In such case the cable needs to be pulled up by carefully applying a force to the anchor point of the cable. The anchor point is anchored to the cable strength member and is the only point where a pulling force should be applied. Therefore if the cable is to be retrieved from mud filled boreholes it needs to be ordered with a number of anchor points along the cable.

Data acquisition

To perform the survey, in short proceed as follows:

- Connect the borehole cables to the switch box.
- Connect land cables to the switch box or to the instrument.
- Connect the instrument to one battery.
- Perform a contact resistance test.
- If the result of the contact resistance test shows that the contact resistance values are between 50-1,000 Ω connect another boost battery to the

SuperSting. Note that the boost battery will only be effective in the range 50-1,000 Ω . For values below or above this range the boost battery will not add anything to the survey.

- Set up the SuperSting with correct desired array, time interval, current etc.
- Start the measurement sequence.
- Once the data is collected you can download the information to a field computer or a main office computer back at the office.
- Use the EarthImager 2D or 3D software to invert the data and obtain the result.

For a 3D survey proceed as above and then disconnect the two cables you just measured from and attach the next survey cables, so that you will get a 3D volumetric resistivity distribution when inverting the two or more sets of collected data. Follow the same procedure again until all combinations of boreholes are measured (see Figure 2).

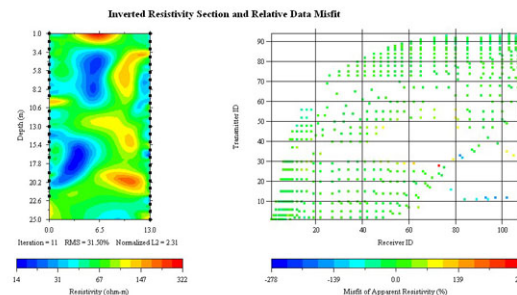


Figure 9 Result of a borehole to borehole survey (left picture) without surface electrodes. The picture to the right shows the misfit between measured data and inverted data.

Data processing

Once the data has been recorded it is downloaded to a computer using the Administrator software. The downloaded file has the extension .stg.

Recorded data is in the format of apparent resistivity. Apparent resistivity can be considered a weighted average of the resistivity distribution between the four measuring electrodes. In order to create a resistivity image or resistivity volumetric distribution the apparent resistivity data needs to be inverted using our EarthImager 2D or 3D software.

The EarthImager software directly reads downloaded stg-files. By simply clicking on “Settings” and select “Cross-Borehole ERT” default settings, all settings suitable for the inversion process of borehole resistivity data are set. The inversion processing is then started by clicking on the inversion start button. The final result is presented as a colorized section between the boreholes.

Data interpretation

The result of the survey is an image in terms of resistivity between the two bore holes (2D), or a volumetric resistivity distribution (3D.)

Resistivity is a material property and different material, geological and others, have different resistivity. The table to the right shows the resistivity of some common materials found in nature.

The most important factors which affect the resistivity of different geological material are:

- Porosity
- Moisture content
- Dissolved electrolytes
- Temperature (resistivity decreases with increasing temperature)
- Conductivity of minerals

Because the geological formations vary in porosity, moisture content, temperature and mineral composition even within the same material, the resistivity typically covers a wide range.

Materials	Resistivity (ohm-m)
Tap water	20 – 30
Sea water	~ 0.2
Saline water (3%)	0.15
Saline water (20%)	0.05
Surface water (sediments)	1 – 100
Surface water (igneous rocks)	0.1 – 3,000
Natural water (sediments)	1 – 100 (average 3)
Natural water (igneous rocks)	0.5 – 150 (average 9)
Clay	5 – 150
Sand (valley)	360 – 1,500
Sand (dunes)	6,200 – 7,700
Gravel	480 – 900
Limestone	350 – 6,000
Sandstone (consolidated)	1,000 – 4,000
Igneous rock	100 – 1,000,000

It is therefore important to know the geology in the area of investigation or have geological information from a borehole in the area.

For example, the resistivity of limestone varies within a wide range. If you know you are in a limestone area, where karst is common, you may or may not find a conductive layer near the surface. This layer is most likely a clay rich weathering product of the limestone. The limestone may appear below this layer as a formation with higher resistivity, maybe in the range of several 1,000 Ω meter.

Within this karstic limestone formation, there may be fractures, air filled voids (caves), collapsed sinkholes etc. Fractures may appear as elongated linear structures with lower resistivity than the limestone, because most likely they contain moisture and clay material. Collapsed sinkholes within the limestone typically show low resistivity by the same reason.

Air filled voids or caves will show high resistivity because of the high resistivity of the air.

When interpreting resistivity data, it is important to understand how the image is created. The algorithm used in the EarthImager is a “smoothing algorithm” meaning that a target will be delineated by a number of equi-resistivity lines. The lines describe the transition from one material to the other. However if a target is small enough, the equi-resistivity lines will not reach the target resistivity.

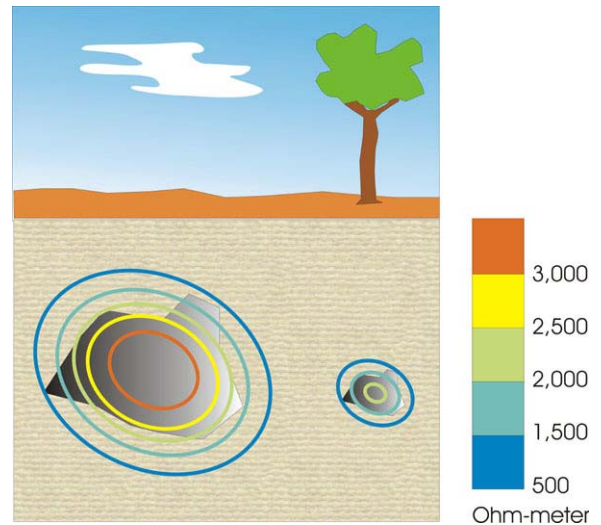


Figure 10 Two different size air filled caves. The equi-resistivity lines at the small cavity to the right do not reach the value of the material (air) in the cave, because the cave is too small.

For example, different size air filled voids will show different value of resistivity. The reason is that the inversion process used in the EarthImager is a “smoothing algorithm” and the resistivity value will never quite reach the value of the material in a small cave, in this case air.

- The equi-resistivity lines will outline the target in a general way.
- Targets of the same material, but of different size, will appear to have different resistivity.
- An air filled void will always appear as a high resistive body.
- A water filled void will appear as a less resistive body than an air filled void of the same size.

Note that distilled water has very high resistivity and gradually becomes more conductive (less resistive) with more dissolved solids. Therefore resistivity can be used as a measure of the quality of ground water. The resistivity method is therefore a very good method for mapping salt water intrusion in coastal areas. In a similar way, water with a degree of in-organic and some organic pollutants, will gradually become less resistive with higher concentrations of pollutants.

Frozen water, i.e. ice has a very high resistivity. The resistivity method is therefore very good for mapping permafrost (permanently frozen subsoil) in arctic areas.

Organic compounds like hydrocarbons typically have very high resistivity. However, some scientists have been reporting observation of a conductive zone where hydrocarbons in the ground interface with ground water. It is believed that this effect may be dependent on bacterial activity on the hydrocarbons at the water/hydrocarbon interface. It is therefore expected that hydrocarbons will show up as high resistive areas, maybe in connection with conductive areas.

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