Fracture Characterization Using Resistivity Measured at Different Frequencies in Rocks

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Keywords
Fracture characterization, resistivity, different frequencies, fractured rock, EGS

ABSTRACT

One of the key issues to a successful EGS (Enhanced Geothermal System) is the creation of a great density of fractures. The detection and characterization of the created fractures is crucial in evaluating the geothermal energy resources in such EGS projects. There exist a few methods to evaluate the fractures after stimulation. However, the methods have some limitations. To this end, an approach to detecting and evaluating the fractures using resistivity data measured at different frequencies has been developed in this study. The effects of fractures on resistivity measurements at different frequencies have been investigated as a function of water saturation in rocks with different porosity, permeability, and lithology. Different rocks (Berea, sandstone, greywacke from The Geysers geothermal reservoir) were used in this study. The permeability of the samples ranged from 0.5 to over 1000 md for the matrix. The frequency ranged from 100 to over 100,000 Hz. It was found that the effect of frequency on resistivity is different in rocks with and without fractures, especially in the range of low water saturation. The validity of the Archie equation depends on the existence of fractures, frequency, and the range of water saturation. The relationship between resistivity and water saturation did not follow the Archie equation at low water saturation in some rocks with fractures. Models for characterizing different types of rocks with specific fracture patterns have been established using the resistivity data measured at different frequencies and different water saturations.

1. Introduction

EGS has been investigated widely (Nalla, et al., 2004; Nalla and Shook, 2004; Wang, et al., 2009 and 2010, Hettkamp et al., 2004; Sanjuan, et al., 2006). One of the key issues to a successful EGS is the creation of a great density of fractures. The detection and characterization of the created fractures is crucial in evaluating and developing the geothermal energy resources in such EGS projects. There are a few methods to evaluate the fractures after stimulation. One of these approaches is analytical modeling using production data. Several mathematical models have been reported to characterize the properties of the hydraulic fractures near the wellbore using production data (Cramer, 2003; Soliman et al., 2005; Crafton and Gunderson, 2006). However, these methods have limitations such as the evaluation of the fracture property is just the average of the fractures.

Aguilera (1974) demonstrated a means of detecting and analyzing fractured systems from logs. It appears from the cases considered that the porosity exponent m is an adequate criterion to detect such a system. Pérez-Rosales, et al. (2000) reported a new formulation for determining formation resistivity factors of fractured porous media and showed a model that could fit some of the experimental data.

The frequency dependence of electrical and dielectric properties of rock partially saturated with water has been reported by many researchers (Knight and Nur, 1987; Adisoemarta and Morriss, 1992; Börner, 1997; Bona et al. 2001; Haugland, 2005). Knight and Nur (1987) collected impedance data for eight sandstones at various levels of water saturation...
in the frequency range of 5 Hz to 4 MHz. They found that the real component of dielectric constant of all samples at all levels of saturation showed a clear power-law dependence upon frequency. Comparing the data from the eight sandstone samples at a water saturation of 36%, the magnitude of the frequency dependence was proportional to the surface area-to-volume ratio of the pore space of the sandstones.

Adisoemarta and Morriss (1992) investigated the electrical properties of swelling shales across a wide frequency range from 10 Hz to 1.3 GHz. They found that the resistivity of different types of shales decreased with the increase in frequency from 10 Hz to about 10 KHz but stayed almost constant when the frequency was above 10 KHz. The experimental data presented by Adisoemarta and Morriss (1992) also demonstrated that the effect of frequency on the resistivity was more significant at lower water saturations than at higher water saturations.

In one of the recent studies (Sandler et al, 2009), the resistivity in a sandstone core sample without fractures was measured at three different frequencies of 100, 1000, and 10,000 Hz to investigate the effect of frequency on the measurement of resistivity. In this case, the measured resistivity did not change significantly with frequency.

The relationship between the resistivity index and the water saturation follows Archie’s law (Archie, 1942) in many rocks. The Archie model is expressed as:

\[ I = \frac{R_i}{R_0} = S_w^{-n} \]  

where \( I \) is the resistivity index, \( R_i \) is the resistivity of rock at a water saturation of 100%, \( R_0 \) is the resistivity at a specific water saturation of \( S_w \), and \( n \) is the saturation exponent.

Sandler et al. (2009) then measured the resistivity in a sandstone core sample with one visual fracture at the same three frequencies of 100, 1000, and 10,000 Hz. It was found that there was almost no effect of frequency on the resistivity index in this core when the water saturation was greater than about 25%. However the resistivity index increased with the decrease in frequency when the water saturation was less than about 25%. The effect of frequency on the resistivity index is increasingly significant as the water saturation becomes lower.

In this study, the effects of fractures and frequencies on resistivity as a function of water saturation have been investigated in rocks with different porosity, permeability, and lithology. Models for characterizing different types of rocks with specific fracture patterns have been established using the resistivity data measured at different frequencies and different water saturations. Finally, an approach to detect and evaluate the fractures using resistivity data measured at different frequencies has been developed.

2. Experimental

2.1 Experimental Apparatus

We modified an existing resistivity apparatus in two aspects. Firstly we modified the software for the data acquisition using NI Labview. With the modified version of the software, we could sample the data from both the LCR meter at four different frequencies and the balance simultaneously. Secondly we modified the way that the electrodes contact the core samples. In the past, we used a stainless steel net to create the electrodes and filter paper to make a better contact between the rock and the electrodes. We found that the stainless steel net eroded because of the long time contact with brine. So we replaced the stainless steel net and fixed the net on a PVC plate. We measured the resistance of the net from side to side.
side and corner to corner, and found the measurements to be around 3 ohm. This value could be neglected compared to the resistance of the rocks.

The main challenge that we had was to establish the quantitative relationship between frequency and fracture properties. Our experimental data during the early period of this study did not demonstrate significant differences between one and two artificial fractures. We speculated that the reason could be that the values of the stress applied to the core samples in different tests were not the same. For this reason, we modified the apparatus by installing a strain sensor between the core sample and the end plate for holding the core samples. This allowed us to impose exactly the same force on the electrodes in each experiment. A schematic of the modified apparatus is shown in Figure 1a.

We added a module to provide a convenient means of completing the Wheatstone Bridge circuit used for the strain gauge measurement (see Figure 1a). We then installed the strain gauge system (see Figure 1b).

We could conduct the measurements under the same tightening stress using the modified apparatus. As a result, the variation in contact resistance was reduced.

Another modification we made to the apparatus was to the on-line weighing method for determining the water saturation. Very fine copper cables with a diameter of 0.50 mm were used to connect to the RCL meter for measuring the resistivity of the core sample on-line (without taking the core sample off the balance). We found that the weighing system was much faster and easier to stabilize after replacing the old stiffer cables with these fine wires. The previous difficulty in weighing the core sample (in which the movement of the wires caused the reading of the balance changes with time even though the weight of the core does not change) was finally solved.

2.2 Rock Samples

In this study, more than 12 rock samples were used, including sandstone, granite, and limestone with or without fractures (both natural and artificial fractures). Figure 2 shows all of the core samples used in this study.

The dimensions and the physical properties of the cylindrical core samples are listed in Table 1.

![Sample s1](image)

![Sample s2](image)

**2(a). Homogeneous rock samples (Berea sandstone): s1 and s2 cut from a whole sample (s1 and s2 should have the same properties such as porosity and permeability).**

![Sample I1-1](image)

**2(b). Homogeneous rock sample (Berea sandstone) I1-1.**

![Sample G-1](image)

**2(c). Rock sample with natural fractures (graywacke) G-1**

![Sample L-1](image)

**2(d). Rock sample with natural fractures (graywacke) L-1**

![Sample F-1](image)

**2(e). Rock sample with natural fractures (graywacke) F-1**

**Figures 2(a-e). Photographs of the core samples used in this project.**

<table>
<thead>
<tr>
<th>Sample Types</th>
<th>Sample No.</th>
<th>L (mm)</th>
<th>D (mm)</th>
<th>Dry weight (g)</th>
<th>Wet weight (g)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>homogeneous</td>
<td>S-1</td>
<td>27.12</td>
<td>26.517</td>
<td>31.040</td>
<td>34.130</td>
<td>20.64</td>
</tr>
<tr>
<td></td>
<td>S-2</td>
<td>24.943</td>
<td>26.043</td>
<td>27.990</td>
<td>30.720</td>
<td>20.56</td>
</tr>
<tr>
<td></td>
<td>I1-1</td>
<td>64.0</td>
<td>37.92</td>
<td>152.23</td>
<td>166.30</td>
<td>18.98</td>
</tr>
<tr>
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<td>50.63</td>
<td>449.40</td>
<td>451.13</td>
<td>1.03</td>
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<tr>
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<td>L-1</td>
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</tr>
<tr>
<td></td>
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<td>30.82</td>
<td>50.74</td>
<td>166.56</td>
<td>167.54</td>
<td>1.60</td>
</tr>
</tbody>
</table>
### 2.3 Experimental Procedures

The rock samples had varying degree of fracturing, from unfractured sandstones to fractured geothermal greywacke, with some samples fractured artificially so that the effect of known fractures could be evaluated. Electrodes were constructed by soldering wires to two patches of stainless steel mesh. The wires were connected on one end to an RCL meter (Quad Tech 1715 or IET labs) and on the other end clamped to either side of a sandstone rock via a hand clamp. This was done alternatively with and without a piece of filter paper clamped between the rock end and the stainless steel electrodes and soaked in the same 1% brine solution (NaCl) in which the rocks were saturated. There was no noticeable difference between the experiments with and without filter paper in some of the cases. This entire apparatus was placed upon a rubber sheet on top of a balance with a reading accuracy of 0.01 g and connected to a computer via RS-232 ports. Modified versions of the NI LabView software for both measurement devices were used to gather mass, resistance, and impedance data from the core at 10-minute intervals while water was allowed to evaporate from the core at ambient temperature of about 20°C. Measurements were taken at frequencies of 100, 120, 1000, and 10000 Hz. Note that the experimental data of 120Hz were not analyzed because these data were very close to those measured at 100Hz. Cores were prepared by first evacuating any air from the pore space by placing the cores in a desiccation chamber and lowering the pressure to nearly 100 mTorr. Brine solution prepared in a separate vacuum flask was then released into the desiccation chamber (still under vacuum) and allowed to invade the pore space overnight. Between experiments the cores were dried in a vacuum oven at 22°C.

### 3. Results

We measured the resistance and other electrical properties of the rock samples with and without fractures at different frequencies. The results are discussed in this section.

#### 3.1 Single Homogeneous Rock

We conducted the experiments in the homogeneous core samples after we modified the apparatus by installing the strain gauge to make sure that the force applied between the two ends was the same every time. Figure 3 shows the results in the core sample 11-1. The values of the resistivity index in this rock are the same at different frequencies.

We used two sandstone samples, s1 and s2 to make artificial fractures of different apertures by putting them together using shims of different thickness. We measured the resistivity in s1 to confirm that there is no effect of frequency on the resistivity index at different water saturations in this unfractured rock. The results are shown in Figure 4.

#### 3.2 Two Cylindrical Rocks with Different Fracture Apertures

Core samples s1 and s2 were used to form one fracture by putting them together with shims (plastic) of different thickness in between. The rock system with one layer of plastic shim is shown in Figure 5.

The resistivity index values measured at three different frequencies in samples s1 and s2 with nothing in between are shown in Figure 6(a). Figure 6(b) shows the data of the
resistivity index with one layer of plastic shim in between (fracture aperture is about 0.08 mm). Figure 6(c) shows the data of the resistivity index measured at three different frequencies with two layers of plastic shim (fracture aperture is about 0.16 mm). Figure 6(d) shows the data of the resistivity index measured with three layers of plastic shim in between (fracture aperture is about 0.24 mm).

One can see from the results that the effect of frequency on the resistivity index is different with fractures of different apertures.

Figure 7(a) shows the relationships between resistivity index and water saturation at one frequency (100 Hz) but different fracture apertures. Figure 7(b) demonstrates the results at the frequency of 10 kHz. The red circles represent the
resistivity index measured in samples s1 and s2 with nothing in between (fracture aperture is estimated about 0.04 mm). The blue triangles represent the resistivity index measured with one layer of plastic shim in between (fracture aperture is about 0.08 mm). The pink cross symbols represent the resistivity index measured with three layers of plastic shim in between (fracture aperture is about 0.24 mm).

3.3 Rocks with Natural Fractures

Core sample G-1 was a graywacke rock from The Geysers geothermal field. Some fractures could be observed on the surface of the rock. The results of the resistivity measured at different frequencies in this rock are plotted in Figure 8. The effect of frequency on the resistivity index is obvious. Interestingly the deviation point water saturation (where the resistivity data become different at different frequencies) in this low permeability rock is much greater than that in the high permeability sandstone (see Figure 6).

Core sample L-1 was a different graywacke rock from The Geysers geothermal field. There are some obvious fractures visible on the surface of the rock. The results of the resistivity measured at different frequencies in this rock are shown in Figure 9. The effect of frequency on the resistivity index is similar to that of Core G-1, as shown in Figure 8.

One can also observe that there is a sharp increase in resistivity index during the early period of test when water saturation is close to 100%. The resistivity index vs. water saturation curves go up and down when water saturation is very small. Currently we are not able to find the reason for this phenomenon.

3.4 Patterns of Resistivity Curves in Rocks With Different Types of Fractures

We conducted many experimental measurements of resistivity in different types of rocks. Figure 10 shows the relationships between resistivity Index and water saturation in rocks with different types of fractures. Three patterns have been identified and are described as follows.

Pattern 1 (in rocks without fractures): the values of the resistivity index in rocks without fractures are the same at different frequencies over the entire water saturation ranging from 0 to 100%. The curves of resistivity vs. water saturation at different frequencies overlap (see top left part in Figure 10).

Pattern 2 (in rocks with single artificial fractures): the resistivity index data in rocks with single fractures but different apertures are not the same at different frequencies and the curves of resistivity vs. water saturation at different frequencies do not overlap when the water saturation is less than a specific value (see middle part in Figure 10).

Pattern 3 (in rocks with multiple or natural fractures): the resistivity indices in rocks with multiple or natural fractures are not the same either at different frequencies and the curves of resistivity vs. water saturation at different frequencies do not overlap when the water saturation is less than a specific value (see bottom right part in Figure 10).

Note that the deviation point water saturations in the three different patterns are different. This will be analyzed in more detail in next section. The categories of rocks with fractures may be estimated using the patterns shown in Figure 10 as a template.
3.5 Mathematical Models to Infer the Fracture Properties

The values of resistivity index difference ($\Delta I$: the resistivity index at 100 Hz minus the resistivity index at 10 kHz) at 1% water saturation in the rock systems (composed of two samples s1 and s2) with single fractures but different apertures were determined according to the results shown in Figures 6. The results are plotted in Figure 11. The data points in the rock systems composed of two samples s1 and s2 with three layers of plastic shim are not included in Figure 11 because the water could not be held in the fracture continuously. One can see that $\Delta I$ increases with the increase in the fracture aperture. Using the data shown in Figure 11, the relationship between the fracture aperture and $\Delta I$ can be determined as:

$$F_a = 0.0191 \Delta I$$

(2)

where $F_a$ is the fracture aperture in the units of $\mu$m and $\Delta I$ is the resistivity index difference at a water saturation of 1%. The correlation coefficient of the fit is 0.844. Note that we assumed that the values of fracture aperture and $\Delta I$ are equal to zero in the rocks without fractures.

We noted that the resistivity index data did not follow the Archie equation and there was a threshold value ($I_{th}$) when the water saturation is close to 100%. The values of resistivity index at the frequency of 10 kHz shown in Figures 4, 6 were chosen and plotted in Figure 12.

The values of the threshold value $I_{th}$ were estimated using the data shown in Figure 12 and the results are shown in Figure 13. Using the data shown in Figure 13, the relationship between the fracture aperture and $I_{th}$ can be determined as:

$$F_a = 70.675 \ln(I_{th}) + 16.397$$

(3)

where $F_a$ is the fracture aperture and $I_{th}$ is the threshold resistivity index. The correlation coefficient of the fitting in Figure 13 is 0.9822. The fracture apertures may be inferred using these mathematical models.

4. Discussion

We struggled with the contact resistance during the experimental study. The strategy to solve this problem was to reduce the contact resistance as far as possible and make sure to keep the contact stress constant. The approach to realizing this target was to apply more or less the same force on the two ends.

Further studies are required to make this approach practical in deriving fracture properties in rocks in the field.

5. Conclusions

The following conclusions were obtained according to the theoretical and experimental studies:

1. Experiments were conducted in different types of rocks with and without fractures. The electrical properties were measured at different frequencies and water saturations in rocks with different patterns of fractures, including single artificial fractures with different apertures, multiple and natural fractures without specific structures.

2. It was confirmed that there is an effect of frequency on the resistivity in rocks with artificial or natural fractures over a wide range of frequencies. On the other hand, in rocks without fractures there is almost no effect of frequency on the resistivity index over the entire range of water
saturation. Over a frequency range from 100 to 10,000 Hz, the resistivity index increases with a decrease in frequency in fractured rock when the water saturation is less than a specific threshold value.

3. Different deviation patterns have been identified in rocks with different structures of fractures (single artificial fractures with different apertures and natural fractured systems).

4. The relationships between fracture apertures and electric property parameters of the rocks have been established. Mathematical models have been developed to infer the fracture properties using the measured resistivity data.

5. It is possible to infer fracture properties in rocks using electric parameters measured at different frequencies and water saturations.

Acknowledgement

This research was conducted with financial support to the Stanford Geothermal Program from the US Department of Energy, Award Number DE-EE0005516, the contribution of which is gratefully acknowledged.

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