Electrical resistivity of loose sand during fluid injection processes

Muhammad Bisri Mustofa[1] | **Umar Fauzi[2]** | **Warsa [3]** |
Fourier Dzar Eljabbar Latief[4]

[1]Earth Physics and Complex System,
Faculty of Mathematics and Natural Scieces,
Institut Teknologi Bandung, Indonesia

[2]Applied Geophysics and Exploration,
Faculty of Mining and Petroleum
Engineering, Institut Teknologi Bandung,
Indonesia

[3]Affiliation not available

[4]Affiliation not available

Correspondence
Author One PhD, Department, Institution,
City, State or Province, Postal Code,
Country
Email: correspondingauthor@email.com

Present address
Department, Institution, City, State or
Province, Postal Code, Country

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Measurement of electrical resistivity of saturated loose sand-pack has been conducted using four-electrode technique and direct current method. Nine samples with three different grain sizes were prepared for the measurement. The water saturation level was increased by physically injecting brine to the samples in three different vertical positions, i.e. bottom, middle and top. Digital image analysis of the sample is also carried out to analyze the microstructure and to estimate several physical properties. The results show that spatial fluid distribution significantly affects the electrical resistivity of the sample. There is an area that has significant contribution for reducing resistivity, which is the area between two potential electrodes. In addition, it is also revealed that samples with large grains have higher resistivity than samples with small grains. This result can be explained by the physical properties of the permeability of the sample and the surface tension phenomena.

Keywords

Electrical resistivity , Distribution spatial of fluid , Grain size , Loose sand , Digital image of sandpack

1. INTRODUCTION

Estimation of electrical resistivity of saturated porous media, such as rocks and soil, has been routinely carried out

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Abbreviations: ABC, a black cat; DEF, doesn't ever fret; GHI, goes home immediately.

in geophysical prospecting since it could be used in determination of water saturation (Picket 1966), identification of fluid type (Fan et al. 2019), and detection of contaminated zone (Pandey and Shukla 2018). Archie's law is mostly used for interpretation of reservoir rock, which links resistivity of rock , porosity , and water saturation *S*, as follow: (Archie 1942)

$$\rho = \phi^{-m} S^{-n} \rho_w \qquad (1)$$

where *m* and *n* are factors determined experimentally. Archie (1942) found the value of *m* varies between 1.8-2.0 for consolidated sandstone and 1.3 for clean unconsolidated sandpack. The value of *n* appears to be close to 2 (Archie 1942). Several studies have found more extensive range for factor *m*: 1.90-3.4 (Lucia 1983); 1.72-4.14 (Verwer, Eberli and Weger 2011); 1.8-2.3 (Ramakrishan et al. 1998) and factor *n* 0.16-1.02 (Taylor and Barker 2006).

Several studies were carried out to understand the electrical resistivity affected by fluid saturation level (Alvarez 1973; Yan, Miao and Cui 2012). Attia, Fratta and Bassiouni (2008) performed that the electrical resistivity of Berea sandstone and Limestone increases as the brine saturation decreases. Taylor and Barker (2002) presented a measurement technique for poorly cemented sandstone, and the results showed that the electrical resistivity decreases significantly in the saturation region below the critical water saturation at approximately 25%. Roberts and Lin (1997) measured the electrical resistivity of saturated Topopah Spring tuff. Water imbibition was carried out in three ways, i.e. by moisture from the air, storing samples in the humidity chamber, and adding water to the sample physically. The results of the measurements denoted that water was interconnected at approximately saturation level of 35%. Knight (1991) reported that resistivity-saturation trends were affected by 'fluid geometry' in which at low saturation, the resistivity decreases rapidly. On the other hand, at the highest saturation, the resistivity gradually decreasing with increasing fluid saturation.

A number of studies were also conducted to evaluate the effect of pore structure (Suman and Knight 1997; Muller-Huber, Schön and Börner 2015) and grain structure (Jackson, Smith and Standford 1978; Torskaya et al. 2014) on electrical resistivity. Muller-Huber, Schön and Börner (2015) investigated the effect of granular pore radius on formation factors (ratio of effective resistivity to fluid resistivity). Pore geometry is expressed as the ratio of pore throat radius and pore body radius. The results showed that electrical resistivity is strongly influenced by pore geometry. Jackson, Smith and Standford (1978) presented the relationship between the particle shape of sand and the electrical resistivity of rocks. Based on the result, the shape of the particle affects the formation factors, in which decreasing sphericity of the grain produces a higher formation factor. Torskaya et al. (2014) modelled rock grain shape with various rock parameters such as grain volume, grain type, grain distribution, and grain size. The formation factor of the rock grain model was calculated where the higher factor cementation of samples, the higher formation factor generates.

A more recent work by Dong et al. (2018) modelled spatial fluid distribution in digital rock pores. There were three distribution models, i.e. adhesive type, cemented type, and scattered type. The results pointed out a different resistivity pattern for each type of distribution. Based on the results obtained by Dong et al. (2019), the spatial distribution of fluid in the pore is indicated to affect electrical resistivity. Further observations are required to analyse the effect of spatial fluid distribution on electrical resistivity. In this study, electrical resistivity measurements were conducted on fluid injected loose sand with different grain sizes in which fluid injection processes were carried out at several different locations to obtain fluid spatial distribution variations.

2. SAMPLE DESCRIPTION AND EXPERIMENTAL PROCEDURE

| 2.1 Sample description

The loose sand used in this study is unconsolidated sand from Ngrayong, Central Java, generally composed of quartz (Niyartama, Fauzi and Fatkhan 2017). The samples were sieved by the USA Standard test sieve (ASTM E11). The samples were dried in the oven first at a temperature of 120º C for 24 hours. Subsequently, the samples are contained in a cylindrical glass, with the height of 10-cm-and the diameter of 3.4-cm. Nine sand packs were used for electrical resistivity measurement. The physical properties of the samples are listed in Table 1.

There are three rock grains sizes (Samples A, B, and C) in which from each group, three relatively similar samples were made. The porosity of the samples is obtained through equation (2)

$$\phi = \frac{V_p}{V_s} = \frac{V_s - V_g}{V_s} \tag{2}$$

where V_p is the volume of the pore sample, V_s is the volume of the sample, and V_g is the total volume of grain. is obtained from the ratio mass of grain and density of grain in which varied between 2.57-2.63 gr/cm^3. The mesh range used in Samples A, B and C are 10/20, 20/40 and 40/60, respectively. Although the grain size is different, the porosity is almost the same for all samples. These samples have relatively high porosity, as reported by Tickel, Mechem and McCurdy (1932), Sparlin (1974), and Das (2008).

Analysis of sample digital images was also carried out using the methodology described in Latief et al. (2017). Three samples, with the height of 2-cm and the diameter of 1-cm, were scanned to obtain a high-resolution image for purposes of microstructure analysis and assumed to represent the sample to be measured. The scanning process was perfomed using the following parameters: The Source-sample distance 54.60 mm, voltage 65 kV, current 80 µA, exposure 125 ms, rotation step 0.8 ̄degree, 180° scan rotation, and used a 0.1 mm aluminium filter.

| 2.2 Experimental Set-up

The laboratory resistivity measurements were carried out using a four-electrode technique, where two 2-mm thick copper plates were used for current electrodes and two stainless steel rings were used for potential electrodes. The technique was selected to minimize the effects of polarization (Campanella and Weemees 1990; Abu-Hassanein, Benson and Blotz 1996; Verwer, Eberli and Weger 2011). Connections between resistivity meter and sample container are shown in Figure 1.

In this study, we use direct current method to measure the electrical resistivity of saturated samples. The calibration of the instrument was carried out by measuring the copper and brass cylinders and compared with a reference, to ensure that measuring instrument is appropriately calibrated (see Table 2). Electrical resistivity measurements were also conducted on a sandstone sample using the direct current (DC) and alternating current (AC) methods as a comparison, where the measurement results showed the same resistivity values for both DC and AC (see Table 2). This comparison was also conducted by Löfgren and Neretnieks (2003), to measure the formation factors using the AC and DC.

| 2.3 Experimental Procedure

The measurements were initially conducted on the dry samples. Subsequent to that, the measurements were conducted on the saturated samples where the injected fluid is a green coloured 6% NaCl brine solution (conductivity of 1.196 mS/cm), and the fluid is injected at around 20%, 40%, 60%, 80% and 100% saturation level. The brine was injected at three different vertical positions, i.e., the bottom of the sample (between electrodes C1 and P1, will be further referred as sample Ax, Bx, and Cx); the middle of the sample (between two potential electrodes P1 and P2, will be further referred as sample Ay, By, and Cy); and the top of the sample (between electrodes P2 and C2, will be further referred as sample Az, Bz, and Cz). See Figure 1 for the illustration of the injection position.

The preliminary research was conducted to examine the relationship between the electrical resistivity with respect to time. It was found that for a single value of saturation, the electrical resistivity is decreased over time as shown in Figure 2. The electrical resistivity decreases until it reaches a constant point (the resistivity is nearly unchanged). The observed changes in resistivity over time are predicted due to the changes in the spatial fluid distribution inside the pore structure so that the electrical resistivity reaches a constant value when there is no longer significant change in the spatial fluid distribution inside the pore.

In order to clearly observed the phenomena, multiple consecutive measurements were done every 1000 minutes. The average of the resistivity when the value was no longer change significantly, was used to plot the log resistivity vs brine saturation (denoted with a red dot in Figure 2). In Figure 2, the electrical resistivity was observed to reach a constant value after approximately 6000 minutes after the injection. Table 3 shows the time required to obtain constant resistivity on each sample where sat 1, sat 2, …, sat 5 is the order of imbibition in each sample. There is no specific pattern regarding the time to reach a constant resistivity. However, there is a tendency that for higher saturation, the time to reach the constant value is relatively shorter.

3. EXPERIMENTAL RESULT

| 3.1 Influences of injection location

The result of measurement on sample A, sample B, and sample C are displayed in Figure 3 as plots of log electrical resistivity (ρ_r) versus brine saturation (S_w). Figure 3a shows data from sample Ax and Ay; Figure 3b from Sample Bx and By; Figure 3c from Sample Cx and Cy. In the three sample categories, log ρ_r dependency on S_w is quite similar. The resistivity of the samples that are injected with brine from the bottom position is always higher than the samples that are injected from the middle position until it reaches a certain point. We defined this point as critical brine saturation S_w^o in which for sample A and sample C, critical brine saturation is approximately at S_w^o = 0.70; for sample B, the critical brine saturation is about S_w^o = 0.6. Beyond this critical brine saturation, the resistivity of the three sample categories is relatively the same up to the full saturation state. Based on these results, the three regions can be defined in the data as follows: region 1, at low brine saturation; region 2, at intermediate brine saturation; region 3, at the highest brine saturation. Regions 1 and 2 are prior to the critical brine saturation, while region 3 is beyond the critical brine saturation up to the fully saturated state.

In region 1, the electrical resistivity decreases with increasing brine saturation for the three data sets. There are differences in the pattern of the decrease in the resistivity between each sample that are injected brine from the bottom position which will be further referred as samples X (Ax, Bx, and Cx) and the samples that are injected brine from the bottom position which will be further referred as samples Y (Ay, By, and Cy). In this region, the resistivity of samples X is slowly decreasing, on the other hand, the resistivity of samples Y decreases rapidly. In region 2, the

opposite condition occurs where the resistivity of samples X decreases dramatically by approximately two orders of magnitude, while the resistivity of samples Y decreases monotonously. Region 3 is initiated with a critical brine saturation until the state of full saturation: sample A in the range Sw = 0.78-1.00; sample B in the range Sw = 0.59-1.00; sample C in the range Sw = 0.73-1.00. In this region, the change of resistivity of all samples is considered insignificant, compared to other regions.

| 3.2 Influence of grain size

In this study, log electrical resistivity (ρ_r) versus brine saturation (S_w) was also plotted as a function of grain size, as displayed in Figure 4. Figure 4a and 4b are the data obtained from the samples that are injected with brine from the bottom position (Samples X) and middle position (Samples Y) respectively. . The results show that Sample X and Y have different ρ vs S_w pattern. For Samples X (Figure 4a), we can define three regions in the data to explain the relationship between resistivity vs brine saturation. In the region 1 (at low saturations, Sw = 0-0.4), the electrical resistivity decreases gradually. In the region 2 (at intermediate saturation, Sw = 0.4-0.8), the resistivity decreases rapidly approximately in three orders of magnitude. In the region 3, at higher saturation, the resistivity tends not to change, even almost constant. For Samples Y (Figure 4b), the resistivity decreases significantly up to saturation of 0.8. Afterwards, the resistivity changes gradually until the state of full saturation for all samples. For both Samples X and Samples Y, the critical brine saturation occurs at approximately saturation of 0.8. While the log ρ_r vs Sw pattern of the two sample categories is unique, there are similarities between the two sample categories. In region before the critical brine saturation, the resistivity of samples with larger grain size is always higher than that of with the smaller grain size.

| 3.3 Physical properties of sample from digital images

The results of the three samples scanning can be seen in Figure 5. Based on the digital images, it can be seen that Sample A has the largest grain size compared to Sample B and Sample C. The grain size of Sample B seems to be slightly larger than the grain size of Sample C, although no significant difference can be seen. Estimation of porosity through digital images and measurement showed good agreement, as shown in Table 4.

Beside calculating the bulk porosity, 2D porosity analysis was also performed on each vertical slice of the image. 2D porosity calculation results show that the samples are quite homogeneous (see Figure 6b). Thus, the injected brine is assumed to have the same behaviour in all pores of the sample. In addition, the pore size distribution of the samples was also analysed (see Fig. 6a). The pore size distribution which was calculated is both the connected and isolated pores. However, the isolated pores are most unlikely exist due to the fact that the sample is constructed from unconsolidated sand. In Sample A, the pore size is quite large, as the consequences of large grain sizes. As for Sample B and C, the pore size distribution is quite similar, although for Sample B it is slightly larger than Sample C. Pore size distribution shows a similar tendency, where the peak is higher for the smaller grain size.

The result from digital image analysis of the scanned samples is summarized in Table 4. The specific surface area S is defined as the ratio between the surface area of the grains to the total total volume of the sample. Specific surfaces area is used to calculate the permeability which obtained through the Kozeny-Carman equation, as shown in the equation (3) (Mavko, Murkeji and Dvorkin 2009)

$$k = \frac{1}{2} \frac{\phi^3}{\tau^2 S^2}$$ (3)

with k, S, and τ are permeability (Darcy), specific surface area (1/mm), and tortuosity respectively. The permeability obtained is inversely proportional to the grain size. The larger the grain size: the higher the permeability. The permeability of sample A, which has the largest grain size, is 613.89 Darcy, Sample B and Sample C have 193.93 Darcy and 127.48 Darcy respectively. These samples have relatively high permeability, especially Sample A. The permeability is in accordance with several previous studies (Sparlin 1974; Gurley, Copelang and Hendrick 1977; Cocales 1992).

4. ANALYSIS AND INTERPRETATION DATA

| 4.1 Influences of injection location

In this study, there are two independent variables: the level of saturation and the spatial distribution of brine. During the measurements, the saturation level and the distribution of brine were varied in which the geometry (spatial distribution) of brine and air changes. The resistivity of the samples decreases with increasing brine saturation. While different resistivities are obtained due to variations in the spatial brine distribution, the change in the electrical resistivity can be predicted to occur due to changes in the brine geometry.

In Figure 3, the resistivity of samples Y is always lower than that of samples X. The results indicate that there are areas in between the two potential electrodes that significantly reduce the resistivity. To confirm this, we present the measurement results on sample C at sat 1 (see Table 3), with direct measurements right after the brine injection. Figure 7 shows the change of resistivity over time for Sample C, on the first brine injection (sat1). In the initial measurements, assuming the fluid is right at the injection site, it shows a noticeable difference that the brine in the area of two potential electrodes significantly decreases the electrical resistivity.

To strengthen this hypothesis, measurements were taken on three samples that were horizontally positioned. All the three samples were injected with 10 ml brine in three different positions: on the left side of the sample; on the middle of the sample; and on the right side of the sample. Resistivity measurements were made just after the brine injection, assuming the brine is still right at the injection site. Figure 8 shows the results of from the measurement of the three samples in a dry and partially saturated state. In the dry condition, all the three samples have the same resistivity, but just after the brine injection, the resistivity of the middle sample drops intensely, while for the left and the right samples, the resistivity only decrease slightly and both the left and the right-side samples have almost equal resistivity.

The result strongly suggests that the area between the two potential electrodes is the area which significantly contributes for reducing electrical resistivity. Consequently, in the measurement of the resistivity, the samples that were injected with brine from the middle is always lower than that of injected with brine from bottom. This behaviour only applies up to the critical brine saturation, the area beyond the critical brine saturation, the resistivity tends to be relatively the same for all samples, both the ones that are injected from the middle and the bottom.

Referring to Figure 3, if it is assumed that the injected brine occupies uniformly into the pores of the samples, it can be predicted that the critical brine saturation occurs when the distribution of the brine has passed through the area above the potential electrode (see Figure 9). Based on this analysis, we can say that after passing through the area above the upper potential electrode (P2), the critical brine saturation occurs, where the potential will change gradually, and the resistivity tends to be the same between the samples that injected with brine from the middle and bottom positions. This explains the trend in the ρ vs Sw for all sample X (see Figure 4a). In region 1, the brine is still below the potential electrode (P1), characterized by the monotonically decreased in resistivity. For region 2, the brine has entered the area between the two potential electrodes (P1 & P2), which is the area which significantly contributes

for reducing the resistivity. It can be seen that the slope of the graph in region two is steep. In region 3, the brine has passed the upper potential electrode (P2), thus the resistivity changes gradually. See Figure 9 for an illustration of the brine state for each region of plot in Figure 4a.

| 4.2 Influence of grain size

One of the objectives of this study is to investigate the effect of grain size to the resistivity of partially saturated samples. Figure 4 shows ρ_r vs Sw for three different grain sizes, where the resistivity of the samples with smaller grains is always lower than samples with larger grains in the area before the critical brine saturation. The difference in pore structure in the sample that must be considered in assessing changes in the resistivity of the samples. The physical properties of the samples which are listed in Table 1 and Table 4 are important for analysing the samples' structure. One of the prominent physical properties between samples A, B, and C is the permeability, where the samples that have the largest grain size have the highest permeability. Note that permeability is the ability of the medium to allow fluid to pass through the medium. Thus, referring to Table 4, the injected brine in sample A has the tendency of flowing more easily compared to the other samples.

A notable observation in samples Y at saturation of 0.2 is the fact that in sample Ay, the brine (marked in green) tends to flow immediately and settles in the lower area until a particular time. In contrast, to sample Cy, which has a low permeability, brine tends not to flow and settles right at the injection site. As for Sample By, the permeability is not as large as Sample Ay and also not smaller than Sample Cy, the brine partly flows towards the bottom of the sample and partly holds it right at the injection site (see figure 10).

This phenomenon where the fluid has the tendency of settling in a certain part of the sample, can also be explained by surface tension, which can be calculated by the Wilhelmy equation (Abe, Takiguchi and Tamada 2000)

$$\gamma = \frac{\rho_g g h^2}{2(1 - \sin\theta)} \tag{4}$$

where γ, g, h, and θ are surface tension (N/m), density of grain (kg/m^3), gravitational acceleration (m/s^2), height of the meniscus created, and contact angle of the liquid on the solid (degree) respectively. From this equation, the surface tension of each sample can be obtained, as shown in Table 5. Sample A has a low surface tension, so there is no force to hold the brine around the injected area, thus, the brine can flow easily to the bottom of part of the sample. On the contrary, for Sample C, which has a high surface tension, brine tends to distributed only around the area on the injection. As for sample B, the surface tension is not strong enough to hold a certain amount of brine, so that at 10 ml injection, some of the brine is retained at the injection site and some of the brine flowed to the bottom of the sample.

Based on these observations, we can explain the data in Figure 4b, the sample that injected with brine from the middle position for three different grain sizes. The resistivity of Sample A (the sample with the largest grain size) is always higher than Sample B and Sample C in the area before the critical brine saturation. This result happens because the brine in Sample A tends to fill the pore in the lower position so that the majority of the brine is not in a significant area (between two potential electrodes). In contrast to Sample B and Sample C, the majority of brines are in significant areas. Likewise, the data in Figure 4a, the resistivity of the samples that injected with brine from the bottom position for three different grain sizes. Sample A always fills the lower pore compared to Sample B and Sample C, which sometimes fills the upper pore from the brine injection position. After the brine had passed the critical brine saturation, the brine saturation did not significantly affect the electrical resistivity, both for samples that are injected

from the middle position or the bottom position.

| 4.3 Interpretation resistivity data of the samples that injected with brine from the top position

Measurements have also been made on the samples that was injected with the brine from the top position (Az, Bz, and Cz). The results of the measurements are shown in Figure 11. In Figure 11a, the resistivity of sample Az is always lower than the resistivity of the sample Ax and Ay. Based on the previous analysis, the characteristic of sample A is that it is easy to let the brine pass through the pore space. Thus, in this case, the brine flows to the bottom of the sample while also wets some parts of the sample. The data in Figure 11a can be interpreted that for sample Az, the area between the two potential electrodes (P1 &P2) has higher fraction of brine that wets the sample compared to the sample Ay and Ax.

In Figure 11b, the resistivity of the sample Bz at low saturation, is higher than that of the sample By. In this situation, the brine is kept above the upper potential electrode (P2), due to the small pore size and low permeability. However, after saturation is increased, the brine eventually seeps down to the bottom part of the sample. Thus, in the sample Bz, the brine is more dominant in the area between the two potential electrodes compared to sample By. Consequently, the resistivity of the Bz sample is lower than that in sample By in this area. Subsequently, after the brine passes the upper potential electrode (P2), the resistivity of all samples tends to be the same (critical brine saturation).

In Figure 11c, the resistivity of sample Cz is always higher than the resistivity of the sample Cy in the area before the critical brine saturation. Sample B has low permeability and small pore size, thus, brine tends to be kept at the injection site. As the consequence, that the area between the two potential electrodes has a higher fraction of fluid that wets the grains in sample Ay compared to sample Ax and Az.

| 4.4 Calculation of electrical resistivity

The calculation of resistivity has been done by using the Archie's equation and finite element method (FEM). The FEM method is applied to solve the Laplace equation (Garboczi 1998), where the input for the FEM is the digital images which were obtained from sample scanning using micro-CT. The brine saturation model is a simple fluid filling model developed by Fauzi, Mustofa, and Latief (2019). Fluid fills the pore space with a simple mechanism where the pore is gradually replaced with fluid up to a certain level of saturation. Electrical resistivity calculation results are shown in Figure 12.

Based on the results, the Archie equation and FEM only agrees with the experimental data on the samples that were injected with brine from the top position for all sample and samples, as well as the ones that were injected with brine from the middle for Sample B and Sample C. The m cementation exponents obtained were 1.9, and the saturation exponents obtained were 1.9. For the sample where the brine was injected from the bottom position, there are no similar trend which can be explained by the Archie equation and FEM method at all. These phenomena show that the spatial distribution of brine, which is the most important part in conducting electricity in the sandpack, has a very significant effect, i.e., areas that do not have a sufficiently good spatial distribution of brine, cannot be explained or approached by the Archie equation and FEM method.

5. CONCLUSION

The result of electrical resistivity measurement of sandpacks using a four-electrode technique have shown that the spatial distribution of brine in the pore space, significantly affects the measurement of electrical resistivity. If the brine has sufficiently good spatial distribution in the area between the two potential electrodes (P1 and P2), the resistivity will be decreased significantly the saturation level increases. Meanwhile, if the brine is distributed mostly in the outside of the area between the two potential electrodes, the resistivity is not considerably reduced. In addition, observations of partial saturation measurement suggest that the critical brine saturation occurs when the brine spatial distribution has passed the upper electrode potential (P1) at exact saturation around 0.7–0.8 for all samples.

Electrical resistivity in the samples that have larger grain sizes is always higher than that of with the smaller grain sizes in the region before the critical brine saturation. This result is related to the permeability of the samples and the surface tension between brine and grain. Moreover, the calculation of electrical resistivity through Archie's equation and finite element method only applies to samples that have a good brine distribution in the area between two potential electrodes.

6. ACKNOWLEDGMENTS

7. FIGURES

FIGURE 1 Experimental set-up for the measurement of electrical resistivity where C1 and C2 are electrical current electrodes, and P1 and P2 are potential electrodes. The X, Y, and Z indicates the position of the brine injection (X for the bottom position, Y for the middle position, and Z for the top position).

FIGURE 2 Measurement of electrical resistivity in copper and brass cylinders, and comparison between DC and AC resistivity measurements of saturated sandpack.

FIGURE 3 Log resistivity vs brine saturation: (a) Samples A with mesh size 10/20; (b) Sample B with mesh size 20-40; (c) Sample C with mesh size 40-60.

FIGURE 4 Log resistivity vs brine saturation: (a) Samples X that injected with brine from bottom position; (b) Samples Y that injected with brine from middle position.

FIGURE 5 2-D slices of digital sample images with same image scales: (a) sample A; (b) sample B; (c) sample C. 3-D digital sample images: (d) sample A; (e) sample B; (f) sample C.

FIGURE 6 Digital image analysis: (a) pore size distribution of Samples A, B, and C; (b) 2-D porosity calculation where the dashed line is the value of bulk porosity. **FIGURE 7** Log resitivity vs time data of sample Bx and By in first saturation and measurements are made right after brine injection.

FIGURE 8 Resistivity measurements of the three horizontal samples on dry condition and saturated. (a) left-side; (b) middle; (c) right-side. The green colour is the brine injected into the samples

FIGURE 9   Illustration of saturated samples: (a) the brine is below the potential electrode P1 (region 1); (b) the brine is between two potential electrodes P1 and P2 (region 2); (c) the brine passes through the potential electrode P2 (region 3).

FIGURE 10   Observation on the samples that injected with brine from the middle position: (a) sample A; (b) sample B; (c) sample C.

FIGURE 11   Log resistivity vs brine: (a) samples A; (c) sample B; (c) sample C.

FIGURE 12   Calculation of electrical resistivity: (a) samples A; (c) sample B; (c) sample C.

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8. TABLES

TABLE 1   Physical properties of samples.

TABLE 2   Measurement of electrical resistivity in copper and brass cylinders, and comparison between DC and AC resistivity measurements of saturated sandpack.

TABLE 3   The time to reach constant resistivity for each saturation.

TABLE 4   Physical properties of samples that obtained from digital image analysis.

TABLE 5   Contact angle and surface tension of Sample A, B, and C.

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