Calculating the electrical conductivity of digital rocks based on two-dimensional images

Introduction

Electrical conductivity is an important geophysical parameter to characterize the electrical rock properties and play a significant role in geological resource exploration and logging interpretation. With the development of digital rock physics technique, it is of increasingly theoretical and practical importance to determine the electrical conductivity of rocks quickly and accurately. The accurate acquisition of three-dimensional (3D) microstructure of rock is the key to the calculation of the electrical conductivity by digital rock physics technique. However, it is complicated and time-consuming to obtain the 3D microstructure by traditional methods. In contrast, two-dimensional (2D) rock images are relatively widely and routinely available. It is therefore of considerable interest to address whether it is possible to use 2D images to gain information on the corresponding properties of the 3D rocks. Fortunately, some scholars have successfully estimated the elastic properties and permeability of rocks using 2D rock images (e.g., Saxena and Mavko, 2015; Saxena et al., 2017). However, whether the electrical conductivity of rocks can be estimated by using 2D microstructure information remains largely unaddressed.

In order to calculate the electrical conductivity of rocks conveniently and quickly by digital rock physics technique, the conductivity relationship between 2D digital rock samples and 3D digital rocks is studied in this work. Based on the 3D microstructure of 3 sandstones obtained by micro X-ray computer tomography (CT), we have established the original digital rocks. New 3D digital rock samples with larger porosity are generated by expanding the pores of the rocks digitally. On this basis, the electrical conductivity of the 3D digital rock samples and the corresponding 2D digital rocks are calculated by using finite element method, and we further characterize the relationship between the rock electrical conductivity and porosity by Archie equation, and the corresponding cementation coefficients are obtained. Taking the connection between 2D and 3D cementation coefficient as a link, the relationship between the conductivity and porosity of 3D digital rocks can be determined through the relationship between conductivity and porosity obtained from fast calculation of 2D images, and the conductivity of 3D digital rocks can then be calculated.

Method

In order to establish the conductivity relationship between 3D and 2D digital rock samples, we need to correlate the conductivity and porosity of the corresponding digital rocks, that is, to calculate the conductivity of 3D and 2D digital rocks with different porosity by finite element method. Two Berea sandstones with different porosity (denoted as Berea sandstone 1 and Berea sandstone 2 with porosity of 20.06% and 14.59%, respectively) and one Fontainebleau sandstone (with porosity of 8.87%) were selected for micro CT scanning. Referring to the processing steps of rock CT scanning images by Andrä et al. (2013a, 2013b), we used Avizo software to perform watershed segmentation and other operations to transform grey images into binary digital samples with grain and pore voxels (see "Sample A" of each rock sample in Figure 1). The size of Berea sandstone 1 and Berea sandstone 2 digital samples was 600x600x600 pixels, the size of Fontainebleau sandstone digital samples was 700x700x700 pixels, and the voxel edge length was 1.7 μm. Then, the “Samples B” and “Samples C” with larger porosity were created by digitally reducing the grains of “Sample A” (i.e., the original sample) of the three sandstones by assuming uniform overgrowths on the frame mineral grain surfaces. The 3D digital rock samples and porosity information of Berea sandstone and Fontainebleau sandstone are shown in Figure 1. In addition, the 2D digital rock mentioned in this work was obtained from the xz section of the corresponding 3D digital rock sample shown in Figure 1, which can be regarded as a 3D digital rock with a pixel thickness in the y direction. Finally, based on the finite element method of Garboczi (1998), we calculated the conductivity in the z direction of the above 3D and 2D digital rocks.
Figure 1 Binary digital rocks. For each rock type, "Sample A" is a 3D digital rock obtained by referring to the processing steps of rock CT scanning images by Andrä et al. (2013a, 2013b). "Sample B" and "Sample C" are derived by reducing the grains in "Sample A" resulting in increased porosity. Pores are shown in black and mineral in grey. Voxel edge length for all sandstone samples is 1.7 μm.

Results

Figure 2 shows the relationship between the conductivity and porosity of the 3D digital rocks (large dots in the figure) and the corresponding 2D digital rocks (small dots in the figure) calculated by finite element method. Red, green and blue represent sample A, B and C of each sandstone shown in Figure 1, respectively. The results show that the conductivity of 3D digital rocks increases with the increase of porosity, which is consistent with the variation trend of conductivity with porosity obtained in the laboratory (as shown by the diamond symbol in Figure 2). In addition, due to the differences in porosity, pore distribution and pore connectivity between 2D digital rocks, the overall conductivity results of the 2D digital rocks spread about two orders of magnitude. Even though, the overall conductivity of the 2D digital rocks still increases with the increase of porosity. We further characterize the relationship between the 3D and 2D rock electrical conductivity and porosity by Archie equation, and the corresponding cementation coefficients are obtained. The fitted results are respectively shown in the dashed curve and solid line in Figure 2. The fitted conductivity-porosity relationship of 3D digital rocks and 2D digital rocks can be expressed by the following equations:

\[
\frac{\sigma_{3d}}{\sigma_v} = \phi^{m_{3d}},
\]

\[
\frac{\sigma_{2d}}{\sigma_v} = \phi^{m_{2d}},
\]

where, \(\sigma_{3d}\) and \(\sigma_{2d}\) are the fitted conductivity of 3D digital rock and 2D digital rock, \(\sigma_v\) is the conductivity of fluid in pore, \(m_{3d}\) and \(m_{2d}\) are the cementation coefficient of 3D and 2D digital rock, respectively.
Figure 2 The electrical conductivity versus porosity for different rock samples: (a) Berea sandstone sample 1; (b) Berea sandstone sample 2; and (c) Fontainebleau sandstone sample. Calculations are shown for the 3D digital samples of three rocks (large dot symbols; red, green and blue represent samples A, B and C of each rock, respectively, corresponding to the 3D digital rock samples shown in Figures 1) and the corresponding 2D rocks (smaller dot symbols; red, green and blue represent 2D rocks of samples A, B and C of each rock, respectively). The dashed curve and solid curve represent the conductivity-porosity trend (fitted by Archie equation) of 3D digital samples and the corresponding 2D digital rocks respectively, $m_{3d}$ and $m_{2d}$ are the cementation coefficients. Laboratory data points of rock conductivity are shown in diamond symbol.

Figure 3 Coefficient $M$ of the three rocks versus their measured porosity. The fitted result of $M$ with porosity is shown in black line, and the correlation coefficient $R^2 = 0.9717$.

Based on the cementation coefficients of the 3D and 2D digital rocks shown in Figure 2, We fitted $M$ (the ratio of between the cementation coefficients of the 3D and 2D digital rocks) with the measured porosity $\phi$ of each rock (the correlation coefficient $R^2 = 0.9717$). We find that the coefficient $M$ has a negative linear correlation with the measured rock porosity. The fitted result is shown in Figure 3, and the fitted equation is:

$$M = -1.06 \phi + 0.6257.$$  

Combining equations (1), (2) and (3), the conductivity-porosity relationship of the 3D digital rocks can be obtained by using the conductivity-porosity relationship quickly calculated from 2D images:

$$\frac{\sigma_{3d}}{\sigma_w} = \phi^{m_{3d}} = \phi^{m_{2d}M}.$$  

The conductivity can be further calculated by using the porosity of the 3D digital rock. As shown in Figure 4 (a), we successfully predicted the 3D digital rocks conductivity-porosity relationship (shown as the dotted black curve) of a synthetic sandstone sample by equation (4). In order to show the conductivity results obtained from predicted conductivity-porosity trend of 3D digital rocks more clearly, we compared them with the 3D digital rock conductivity calculated by the finite element method, as shown in Figure 4 (b), and the correlation coefficient $R^2 = 0.9689$, which fully verifies the validity of the proposed calculation method of digital rock electrical conductivity based on 2D images. The proposed method provides a new idea for determining rock electrical conductivity and has broad application prospects in oil and gas exploration and development.
Figure 4 (a) The 3D digital rocks conductivity-porosity trend (the dotted black curve) of a synthetic sandstone sample predicted by equation (4). The large and small dot symbols represent the conductivity of 3D digital samples and the corresponding 2D digital rocks, respectively. (b) The electrical conductivity of 3D digital rocks obtained from predicted conductivity-porosity trend of 3D digital rock samples versus calculated by the finite element method, and the correlation coefficient $R^2 = 0.9689$.

Conclusions

In order to calculate the electrical conductivity of rocks conveniently and quickly by digital rock physics technique, we established 3D digital rocks based on the microscopic information obtained by micro X-ray CT scanning, and then calculated the conductivity of 3D digital rocks and corresponding 2D digital rocks by the finite element method. We further characterized the relationship between the 3D and 2D rock electrical conductivity and porosity by Archie equation, and obtained the corresponding cementation coefficients. Based on the relationship between conductivity and porosity, we studied the conductivity relationship between 2D digital rock samples and 3D digital rocks in this work. We predicted the 3D digital rocks conductivity-porosity relationship of a synthetic sandstone sample, and the electrical conductivity of the 3D digital rocks shows great correlation (correlation coefficient better than 96%) with that calculated from 3D images using finite element method, which verifies the validity of the proposed calculation method of digital rock electrical conductivity based on 2D images.

References


