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Micromechanical approach for electrical resistivity and conductivity of sandstone

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ABSTRACT

The objective of this work is to employ the micromechanical approach for the modeling of the electrical resistivity and of the conductivity of sandstone. This type of rock is considered as a mixture of solid mineral and porous space filled fully or partially by conductive water. The Eshelby's solution of a spheroidal inclusion in a homogeneous matrix is employed. The differential effective medium model (DEM) with different concepts of the microstructure is developed for the calculation of the resistivity. The parametric study clarifies the impact of the microscopic parameters on the macroscopic electrical properties. The simulations are compared with the classical empirical and theoretical approaches as well as with the laboratory measurements. The results show a strong impact of the microstructure (the shape of the pore, the presence of non-conductive fluids in the pore space, the connectivity of conductive fluid) on the macroscopic resistivity and conductivity of sandstone. This approach gives a link between the microscopic physical parameters of the rock and the macroscopic electrical parameters such as the cementation exponent and the electrical formation factor.

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1. Introduction

The electrical resistivity is largely used to interpret the porosity, the geo-pressure (Eaton, 1975), the mineralogy (Hill and Milburn, 1956), the presence of hydrocarbon and the saturation degree of rocks (Ellis and Singer, 2007; Pezard, 1990). As rock is composite porous material, the electrical resistivity depends on its components and on its microstructure (pore shape, cement, saturation degree, conductivity of the grains) (Chinh, 2000; Sen et al., 1981). The contrast between the resistivity of water and that of the solid phases of rock induces a strong porosity sensibility of the overall resistivity (Archie, 1942; Jackson et al., 1978; Wyllie and Gregory, 1953).

Based on laboratory measurements on saturated sandstones, Archie (1942) proposed an empirical formula that is widely used to characterize the impact of the porosity on the electrical resistivity: $R/R_w = \phi^{-m}$ where R, R_w, R/R_w and ϕ are the overall resistivity, the resistivity of water, the relative dimensionless resistivity and the porosity of rocks respectively. The exponent m, so-called cementation exponent (Jackson et al., 1978; Wyllie and Gregory, 1953), is in the range of 1.3 to 4. Many theoretical attempts are realized to explain the Archie's relationship, for instance capillary tube network models (Böttcher et al., 1974; Wyllie and Rose, 1950), percolation theories (Kirkpatrick, 1973; Webman et al., 1975), effective medium theories (Landauer, 1978; Mendelson and Cohen, 1982; Milton, 1985; Norris et al., 1985; Webman et al., 1977) and the self-similar model (Sen et al., 1981). While the Archie's law is relatively simple in practice, the single parameter m is inadequate to describe the complex impact of the microstructure.

To deal with the problem of effective conduction properties and effective elastic properties of composite materials, Eshelby (1957) developed an analytical solution of a single ellipsoidal inclusion in a homogeneous matrix. This solution is a generalization of the classical Maxwell-Garnett and Bruggman theories (Bruggeman, 1935; Maxwell, 1904; Stroud, 1975) that were developed for the special cases of spherical inclusion in homogeneous matrix. Eshelby's solution is developed in different ways to model the effective properties of composite materials (Ortega et al., 2007). The DEM micromechanical approaches are largely used to model the physical properties of rocks (Dormieux et al., 2006; Hornby et al., 1994). This model allows us the identification of the effects of the microstructure on the macroscopic resistivity of the composite. The DEM model starts by an initial continuum matrix and add little by little inclusions into it. This model is effective when there is a connected matrix phase (for example, compacted sandstone can be considered as solid mineral matrix and pore inclusions).

In this study, the DEM model is employed, to deal with the complexity of the microstructure, for the simulation of the electrical resistivity of the sandstone. The impact of each microstructure parameter on the overall electrical resistivity will be clarified. The simulations are compared with the classical empirical and theoretical approaches as well as with the laboratory measurements. This approach provides a link between the microscopic physical parameters and the macroscopic

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electrical parameters such as the cementation exponent or the electrical formation factor.

2. Theoretical framework

Considering the dilute problem of a single ellipsoidal inclusion in an infinity homogeneous matrix (Fig. 1), the Eshelby's solution (Eshelby, 1957; Giraud et al., 2007) Eq. (1) gives the overall conductivity of the mixture.

$$\boldsymbol{C}^{DL} = \boldsymbol{C}_m + f_i(\boldsymbol{C}_i - \boldsymbol{C}_m)\boldsymbol{A}_i^m \tag{1}$$

where $\boldsymbol{C}_m$, $\boldsymbol{C}_i$ and $\boldsymbol{C}^{DL}$ are respectively the conductivity tensor (2nd degree tensor) of the matrix, of the inclusion and of the dilute mixture (Dormieux et al., 2006). f_i is the volume fraction of the inclusion and $\boldsymbol{A}_i^m$ the electric field localization tensor which is calculated by Eq. (2). Where Eq. (1) is the second order unit tensor and $\boldsymbol{P}_i^m$ is the Hill's tensor (Hill, 1965) which depends on the conductivity of the matrix and on the conductivity and the shape of the inclusion.

$$\boldsymbol{A}_i^m = \left[1 + \boldsymbol{P}_i^m(\boldsymbol{C}_i - \boldsymbol{C}_m)\right]^{-1}. \tag{2}$$

Considering the transversely isotropic matrix, the conductivity tensor of the matrix is decomposed to:

$$\boldsymbol{C}_m = C_m^T(1 - \underline{e}_3 \otimes \underline{e}_3) + C_m^N \underline{e}_3 \otimes \underline{e}_3 \tag{3}$$

where the exponents T and N stand for the transversal and the normal part respectively. $\underline{e}_3$ is the unit vector in the anisotropy evolution direction (Fig. 1). Similar decomposition of the conductivity tensor of the inclusion is:

$$\boldsymbol{C}_i = C_i^T(1 - \underline{e}_3 \otimes \underline{e}_3) + C_i^N \underline{e}_3 \otimes \underline{e}_3. \tag{4}$$

Suppose that the matrix and the inclusion have the same anisotropy evolution direction $\underline{e}_3$ which is also the normal vector of the inclusion (penny shape case). In this case, the Hill tensor can be decomposed as:

$$\boldsymbol{P}_i^m = P^T(1 - \underline{e}_3 \otimes \underline{e}_3) + P^N \underline{e}_3 \otimes \underline{e}_3. \tag{5}$$

The electric field localization tensor is then calculated by:

$$\boldsymbol{A}_i^m = A^T(1 - \underline{e}_3 \otimes \underline{e}_3) + A^N \underline{e}_3 \otimes \underline{e}_3 \tag{6}$$
$$A^T = \frac{1}{1 + P^T(C_i^T - C_m^T)}; \quad A^N = \frac{1}{1 + P^N(C_i^N - C_m^N)}.$$

For the case of spheroidal transversely isotropic inclusion in transversely isotropic matrix and the anisotropy evolution direction $\underline{e}_3$ is the same for the inclusion and the matrix, the Hill tensor is calculated by Giraud et al. (2007):

$$\boldsymbol{P}_i^m = P^T(1 - \underline{e}_3 \otimes \underline{e}_3) + P^N \underline{e}_3 \otimes \underline{e}_3 \tag{7}$$
$$P^N = \frac{1-2Q}{C_m^N}; P^T = \frac{Q}{C_m^T}$$

where the parameter Q is a function of the shape and of the anisotropy of the inclusion which is characterized by the parameter $\nu = c * \sqrt{\frac{C_i^N}{C_i^T}}$, with c the aspect ratio of the inclusion (the ratio between the width and the diameter of the plan of the inclusion) (Giraud et al., 2007). For the case when $\nu < 1$ the parameter Q is calculated by:

$$Q = \frac{1}{2} - \frac{\sqrt{1-\nu^2} - \nu \arctan\left(\frac{\sqrt{1-\nu^2}}{\nu}\right)}{2(1-\nu^2)^{3/2}}. \tag{8}$$

Fig. 2 shows the evolution of Q when ν varies from 0 to 1. The limits when $\nu \to 1$ (spherical isotropic inclusion) gives $Q = 1/3$ and when $\nu \to 0$ (disk-like inclusion) gives $Q = 0$.

The dilute solution becomes:

$$\boldsymbol{C}^{DL} = C_{DL}^T(1 - \underline{e}_3 \otimes \underline{e}_3) + C_{DL}^N \underline{e}_3 \otimes \underline{e}_3 \tag{9}$$
$$C_{DL}^T = C_m^T + f_i\left(C_i^T - C_m^T\right)A^T; \; C_{DL}^N = C_m^N + f_i\left(C_i^N - C_m^N\right)A^N$$

The DEM model consists of the use of the dilute solution directly (Eq. (9)). It starts by the matrix and add little by little inclusion into it.

To account for the impact of the orientation distribution of the inclusion, the average overall direction is necessary to calculate the macroscopic conductivity or the macroscopic resistivity of rock. In this study, we consider the case of random distribution of the inclusions. The macroscopic conductivity tensor is isotropic and depends on one conductivity scalar which is calculated by Eq. (10).

$$C = \frac{\left(C^N + 2C^T\right)}{3}. \tag{10}$$

In the next sections, these micromechanical theories will be employed to model the resistivity of saturated and unsaturated sandstones.

3. Modeling of resistivity of saturated and compacted sandstone

We consider the case of compacted sandstone that is a mixture of non-conductive solid matrix (relatively very high resistivity compared

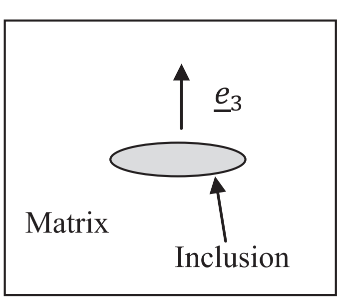

Fig. 1. Matrix-inclusion problem.

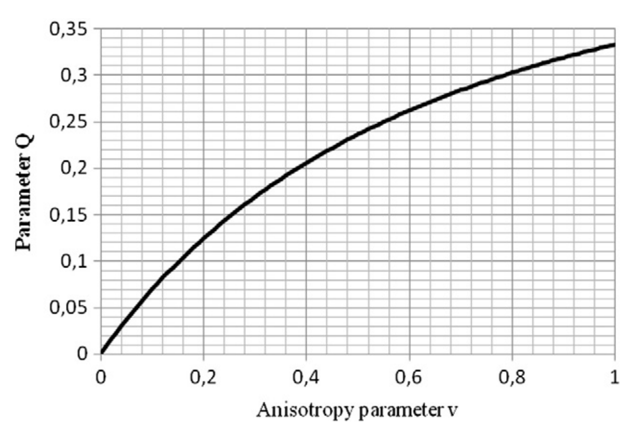

Fig. 2. Dependence of the parameter **Q** on the shape and on the anisotropy of the inclusions.

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