2.5-D Discrete-Dual-Porosity Model for Simulating Geoelectrical Experiments in Fractured Rock

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Abstract

Amongst the numerous existing methods to characterize fractured media, previous work has demonstrated that geoelectrical measurements, acquired either along the Earth's surface or in boreholes, may provide important information regarding fracture network properties. However, the lack of numerical approaches adapted to the strong contrast in geometrical and electrical properties between the fractures and the rock matrix prevents us from systematically exploring the links between geoelectrical measurements and fractured rock properties. To address this issue, we present a highly computationally efficient methodology for the numerical simulation of geoelectrical data in 2.5-D complex fractured domains. Our approach is based upon a discrete-dual-porosity formulation, whereby the fractures and rock matrix are treated separately and coupled through the exchange of electric current between them. Our methodology is validated against standard analytical and finite-element solutions and used to simulate geoelectrical data for a variety of different fracture configurations. This results in demonstrating the sensitivity of these data to important parameters such as the fracture density, depth, and orientation, and in opening new perspectives in terms of the inversion of geoelectrical data in order to characterize fractured rocks.

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1. Framework

Amongst the numerous existing methods to characterize fractured media, previous work has demonstrated that geoelectrical measurements, acquired either along the Earth's surface or in boreholes, may provide important information regarding fracture network properties. However, the lack of numerical approaches adapted to the strong contrast in geometrical and electrical properties between the fractures and the rock matrix prevents us from systematically exploring the links between geoelectrical measurements and fractured rock properties. To address this issue, we present a highly computationally efficient methodology for the numerical simulation of geoelectrical data in 2.5-D complex fractured domains. Our approach is based upon a discrete-dual-porosity formulation, whereby the fractures and rock matrix are treated separately and coupled through the exchange of electric current between them. Our methodology is validated against standard analytical and finite-element solutions and used to simulate geoelectrical data for a variety of different fracture configurations. This results in demonstrating the sensitivity of these data to important parameters such as the fracture density, depth, and orientation, and in opening new perspectives in terms of the inversion of geoelectrical data in order to characterize fractured rocks.

2. Methodological background

General problem formulation

- Under steady-state conditions, the current flow in a 3D domain is governed by the following charge-conservation equation:

$$-\nabla \cdot \left[\sigma(x,y,z)\vec{\nabla}\phi(x,y,z)\right] = I\delta_{x,y,z}(x_0,y_0,z_0),$$

σ: electrical conductivity, ϕ: electric potential, I: electric current injected at position (x_0,y_0,z_0), $\delta(.)$: Dirac delta function.

- Assuming (i) σ constant in the y-direction; (ii) ϕ symmetric in the y-direction; and (iii) current injection in the $y=0$ plane:

$$-\nabla \cdot \left[\sigma(x,z)\vec{\nabla}\bar{\phi}(x,\omega,z)\right] + \omega^2\sigma(x,z)\bar{\phi}(x,\omega,z) = \frac{I}{2}\delta_{x,z}(x_0,z_0),$$

$\bar{\phi}$: Fourier-cosine transform of ϕ, ω: the wavenumber corresponding to the y-coordinate.

- The distributions of potential ϕ and $\bar{\phi}$ are related through:

$$\bar{\phi}(x,\omega,z) = \int_0^\infty \phi(x,y,z)\cos(\omega y)\mathrm{d}y$$

$$\phi(x,y,z) = \frac{2}{\pi}\int_0^\infty \bar{\phi}(x,\omega,z)\cos(\omega y)\mathrm{d}\omega.$$

Discrete-Dual-Porosity (DDP) approach

Electric potential along a fracture segment:

For each 1D fracture-segment, consider the following charge conservation in the Fourier domain:

$$-\sigma_f\partial^2_{x_f}\bar{\phi}_f + \omega^2\sigma_f\bar{\phi}_f = -\bar{Q}_{fm},$$

and the Fourier-cosine transform of the fracture-matrix exchanges:

$$\bar{Q}_{fm} = -\alpha_{fm}(\bar{\phi}_m - \bar{\phi}_f)$$

Modified DFN approach for the fracture network:

At each fracture-intersection node i, charge conservation is expressed as:

$$b^i_f\omega^2\sigma^i_f\bar{\phi}^i_{f|x^k_f=0} - \sigma^i_f\sum_{k=1}^{N_i}\partial_{x^k_f}\bar{\phi}^k_{f|x^k_f=0} = 0.$$

Modified finite-volume approach in the matrix:

For each matrix block, charge conservation is expressed as

$$-\int_{V_{I,J}}\nabla\cdot\left(\sigma_m\vec{\nabla}\bar{\phi}^{I,J}_m\right)\mathrm{d}V + \int_{V_{I,J}}\omega^2\sigma_m\bar{\phi}^{I,J}_m\mathrm{d}V = \int_{V_{I,J}}\bar{Q}^k_{fm}\mathrm{d}V.$$

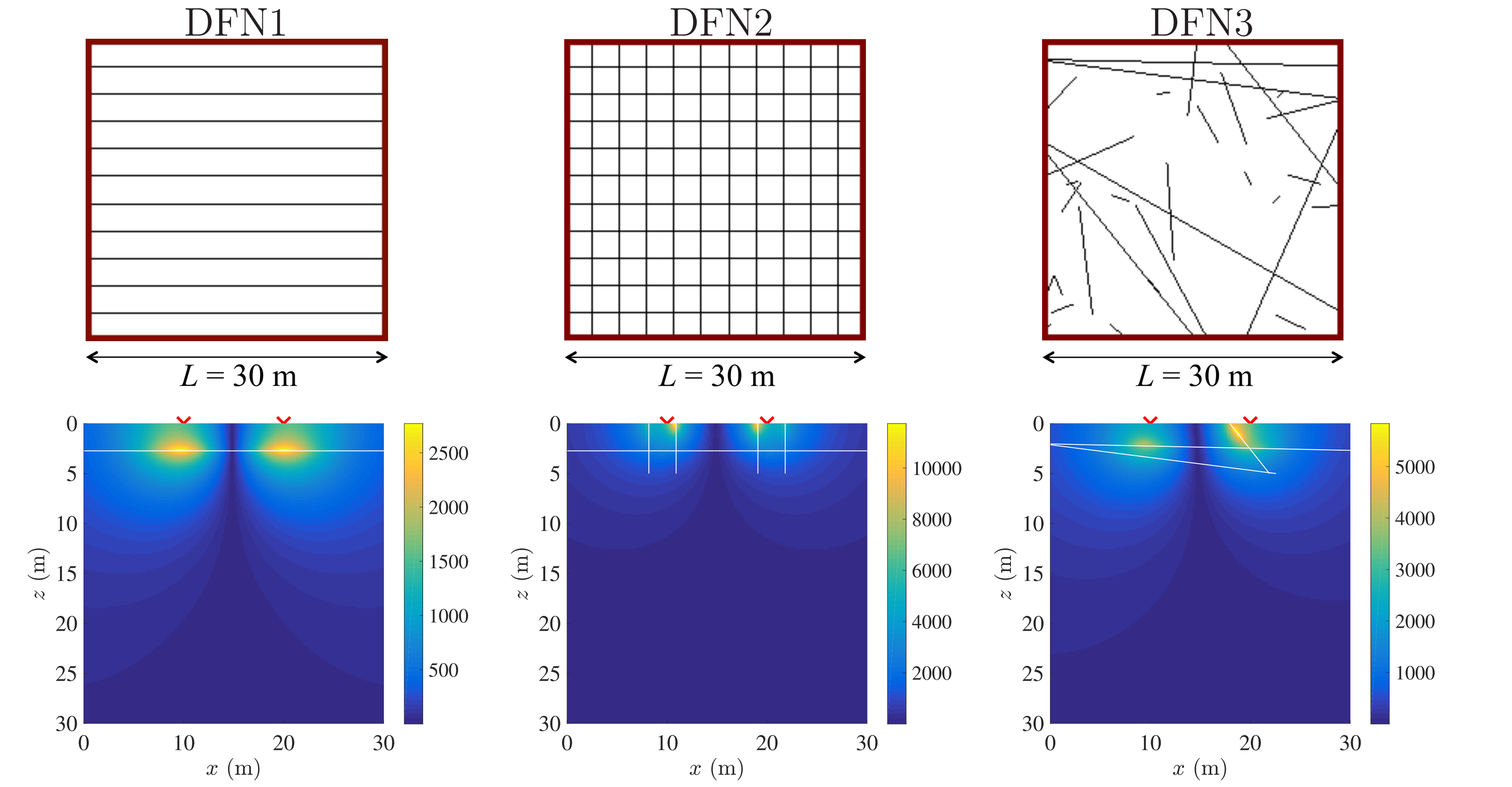
3. Validation of the modeling approach

Parameters

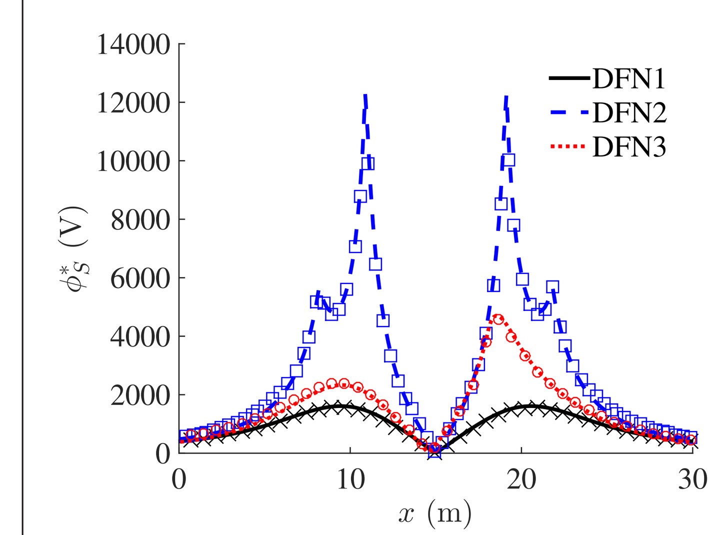
- Domain properties: $\sigma_m = 10^{-5}$ S/m, $\sigma_f = 10^{-2}$ S/m, $b_f = 10^{-3}$ m
- Electric courant injection: $I = 1$ A at $x = 10$ m and $-I$ at $x = 20$ m

Simulations

- Electric potential perturbation (in V) computed with our 2.5D DDP approach in fractured porous domains:



- Electric potential perturbation (in V) at the surface:

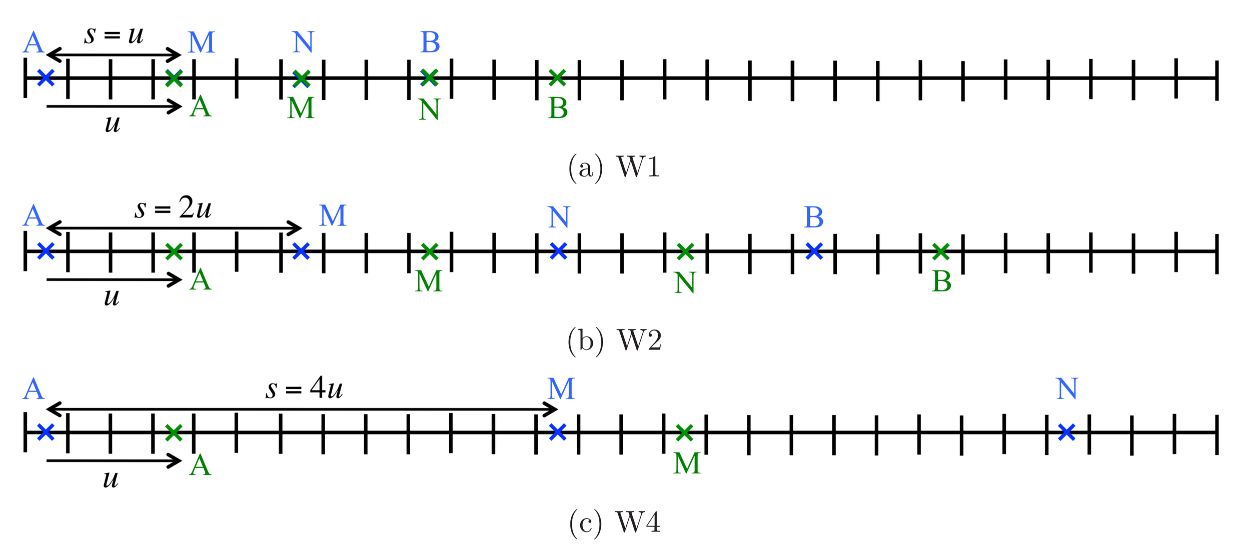


Comparison between our 2.5D DDP approach (symbols) and the COMSOL finite-element solution (lines)

4. Results for complex fractured media

Configurations

- Fractured domains DFN1, DFN2, and DFN3
- Domain properties: $\sigma_m = 10^{-5}$ S/m, $\sigma_f = 10^{-2}$ S/m, $b_f = 10^{-3}$ m
- Wenner electrode configurations: $u = 0.9$ m



(a) W1

(b) W2

(c) W4

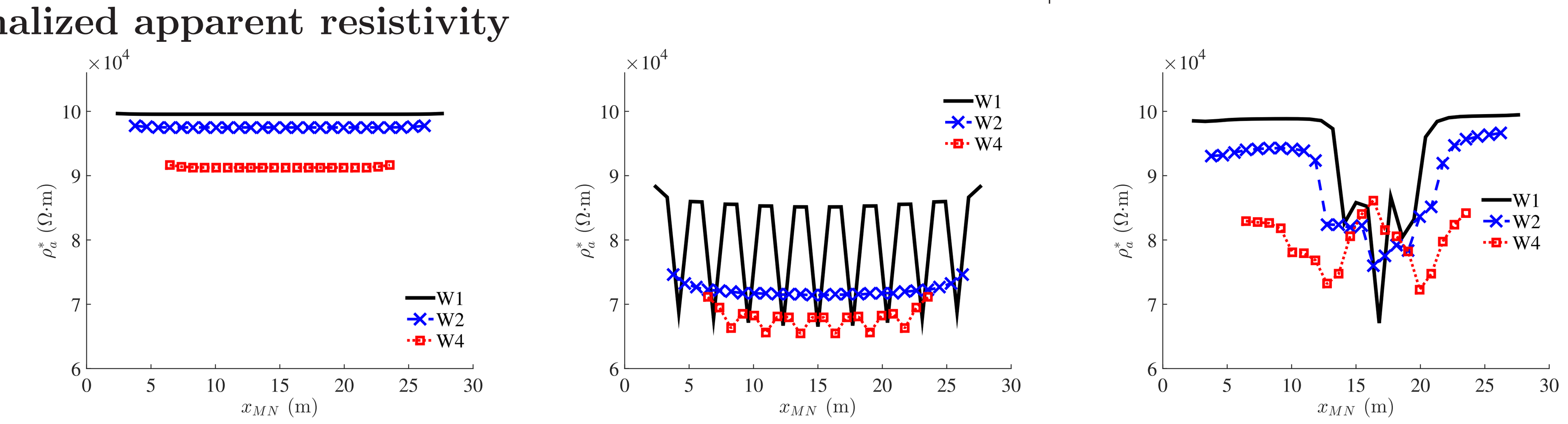
Interpretation

- Normalized apparent resistivity $\rho^*_a = \rho_a \times \rho_m/\rho^m_a$ with $\rho_a = 2\pi s V_{MN}$
- $\rho^*_a(d)$: normalized apparent resistivity evaluated by taking into account only the fractures located above depth d
- Depths of influence d^*: the smallest depth for which $|\rho^*_a(L) - \rho^*_a(d)|/\rho^*_a(L) < 0.1\%$

- Values of d^* (in m) determined with a precision up to 0.1 m for each electrode configuration and fractured domain:

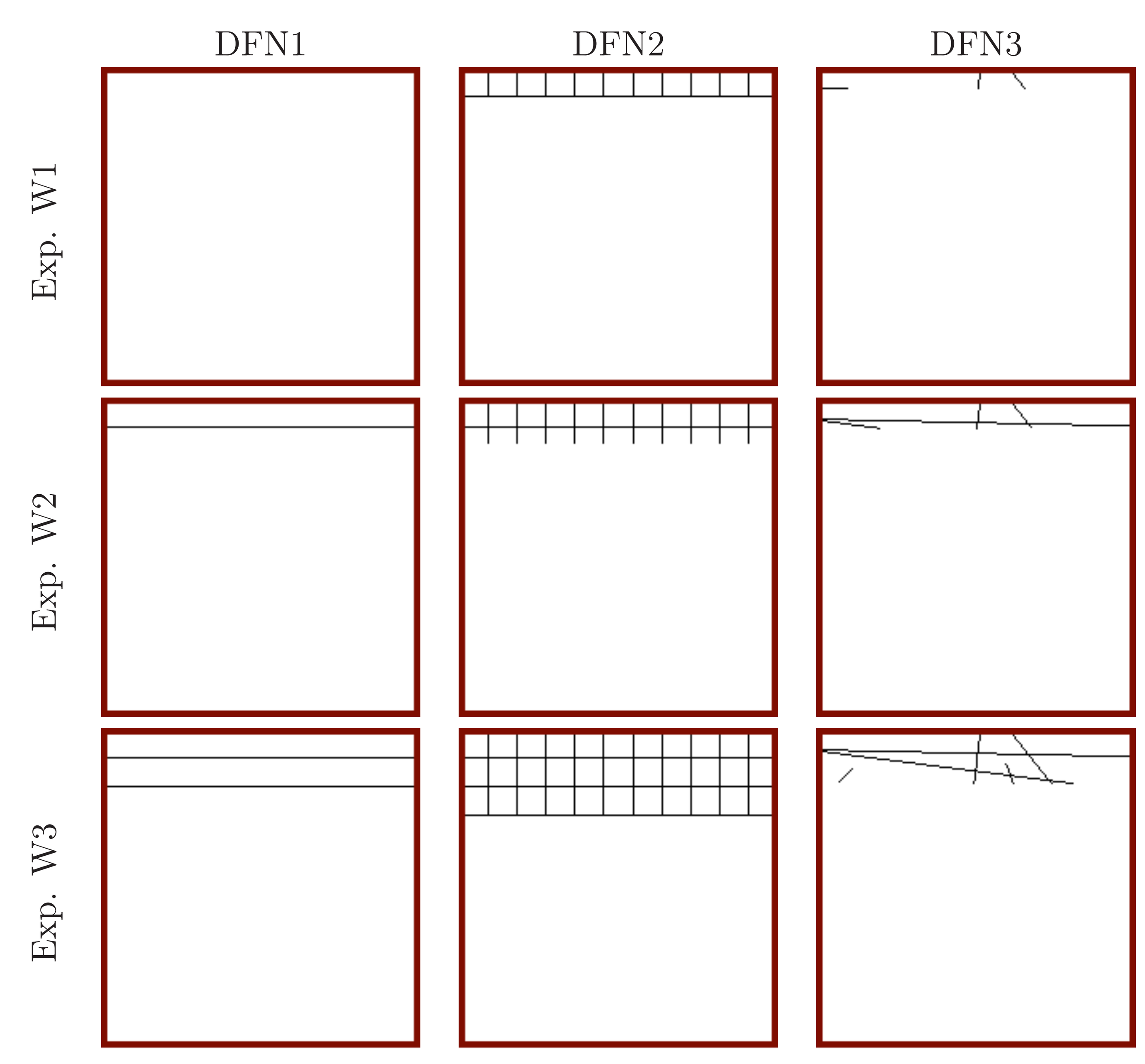
	DFN1	DFN2	DFN3
W1	0	2.8	2.2
W2	2.8	4.3	2.9
W4	5.5	8.2	5.2

Normalized apparent resistivity



DFN1 DFN2 DFN3

Equivalent domains



5. Conclusions

- The computational efficiency of the proposed 2.5D DDP approach makes it an ideal tool to study the **impact of the presence of fractures and of their properties on apparent electrical resistivity** evaluated from ERT surveys
- This approach is well adapted to the **specificities of fractured rocks**, and adequately represents the **physics of point-source injections in heterogeneous domains**
- Comparison with a standard finite-element solution demonstrates the numerical efficiency of our approach, which is **up to 65 times faster**
- The presented results show that (i) a small number of millimeter-scale **fractures can significantly impact the apparent electrical resistivity**; (ii) the presence of **horizontal fractures** results in a **decrease of the measured resistivity** everywhere along the electrode line; and (iii) the presence of **vertical fractures** results in **localized decreases in this resistivity**
- Our results open new perspectives for the **inversion of geoelectrical data** in order to characterize fractured rocks. Future work will include **statistical investigation** for large ranges of fracture-network geometrical properties, and **extension to "real" three-dimensional fractured-rock configurations**.

References

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