Coupling Approach of Lattice Boltzmann Fluid Simulation and Finite Element Analysis of Geophysical Properties: Application to Natural Rock Fracture in Geothermal Area

Sawayama, Kazuki
Department of Earth Resources Engineering, Graduate school of Engineering, Kyushu University

Tsuji, Takeshi
International Institute for Carbon-Neutral Energy Research, Kyushu University

Fujimitsu, Yasuhiro
Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University

https://doi.org/10.15017/2552941

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 5, pp.73-76, 2019-10-24. 九州大学大学院総合理工学府
バージョン：

Coupling Approach of Lattice Boltzmann Fluid Simulation and Finite Element Analysis of Geophysical Properties: Application to Natural Rock Fracture in Geothermal Area

Kazuki Sawayama[1,*], Takeshi Tsuji[2,3], Yasuhiro Fujimitsu[3]
[1]Department of Earth Resources Engineering, Graduate school of Engineering, Kyushu University
[2]International Institute for Carbon-Neutral Energy Research, Kyushu University
[3]Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University
[*]Corresponding author email: k.sawayama0926@mine.kyushu-u.ac.jp

Abstract: *This study develops a new approach which can simultaneously calculate the hydraulic permeability, electrical resistivity and elastic wave velocity from the digital image of natural rock fracture. The digital fracture simulation is applied to natural single fracture which was cored from geothermal area and validate that performance by comparing experimental results. The fluid-flow experiment is conducted in a pressure vessel which simulates the pressure condition of the geothermal area. As a result, resistivity and velocity show thresholds at the same pressure condition (~5 MPa in our study) while decreasing rates of them with aperture opening were different at 0.8 mm or higher aperture condition (decreasing rate of resistivity is ~60 Ωm while that of velocity is ~80 m/s per 0.1 mm aperture change). These behaviors may be controlled by connection or disconnection of the fluid pathway and will be used for subsurface monitoring by using velocity and/or resistivity.*

Keywords: Digital rock physics; Lattice Boltzmann Method; Fracture permeability; Electrical resistivity; Elastic wave velocity.

1. INTRODUCTION

The hydraulic property of crustal fluid is essential to understand the mechanisms of earthquake and fluid reservoir formation (e.g., petroleum and geothermal reservoir). As one of the time-dependent models of earthquake recurrence, fault-valve model has been well known [1]. The fault-valve model describes that the mineral precipitation within faults controls the pore pressure change which can trigger the earthquake recurrence. For estimating this valve-like behavior of faults, fracture permeability plays a key role because the mineral precipitation may preferentially occur at slower fluid-velocity zone. In terms of fluid reservoir development, the permeability estimation is crucial for predicting the fluid production. In addition to permeability, local behavior of fluid-flow (e.g., fluid pathway) within fractures controls preferential-flow and total thermal response in geothermal area [2, 3]. Since permeability decreases with aperture closure [4, 5], fracture aperture condition (opening or closing) should be monitored.

Taira et al. recently observed seismic wave velocity changes in Salton sea geothermal area and interpreted that velocity changes were caused by crack aperture changes [6]. Some magnetotelluric surveys also revealed subsurface aperture opening or closure (e.g., [7]). However, it is unknown that how much aperture changes can demonstrate these changes of geophysical properties. Although there is an enormous amount of studies about electric and elastic properties of rocks (e.g., [8–14]), these geophysical properties of rock fractures have not been well investigated. Recently, Kirkby et al. investigated permeability-resistivity relationship of the rock fracture [15]. Pyrak-Nolte and Nolte proposed universal relationship between elastic and hydraulic properties [16]. However, to the best of our knowledge, relationships between fracture permeability, electrical resistivity and elastic wave velocity have not been revealed yet. Since fracture is anisotropic, these three geophysical parameters should be investigated simultaneously.

In this study, a new approach of Digital Rock Physics is developed that can simultaneously calculate hydraulic permeability, electrical resistivity and elastic wave velocity from the digital image of natural rock fracture by coupling approach of Lattice Boltzmann Method and Finite Element Method. Although there is a great interest of such numerical approach using digitalized rock (so-called Digital Rock Physics), these works mostly uses porous rocks (e.g., sandstone). Present study proposes that Digital Rock Physics can also be applicable to natural rock fracture and confirmed good agreements with experimental results. From the estimated hydraulic permeability, electrical resistivity and elastic wave velocity, the relationships between them as well as mean aperture in the fracture are further discussed.

2. METHOD

2.1 Sample preparation

The numerical simulation and fluid-flow test were carried out using a cylindrical fractured sample (35 mm in diameter and 70 mm long). The sample was obtained from geothermal area and has a natural sheared fracture [17]. For the numerical simulation, a fracture of the sample was digitalized. This digitalized fracture model was created from the surface roughness data of hangingwall and footwall which were obtained by One-shot 3D Measuring Macroscope.

2.2 Numerical simulation

From the digitally created fracture model, three-dimensional fluid flow was calculated by Lattice Boltzmann Method (LBM; e.g., [18–20]). Model sizes of simulations is 224 x 32 x 576 grids. Each grid of x, y and z directions are 0.1 mm. Fluid-flow direction driven by the pressure gradient is along z-direction with periodic boundary. The initial aperture model is determined by assuming that footwall and hangingwall contact at only one point. Consequently, different digital fracture models were prepared by made them closer. After simulating fluid distribution in the fractures by LBM fluid-flow simulation, then elastic wave velocity and electrical resistivity in fluid-saturated fractures were calculated by Finite Element Method (FEM, [21]). Elastic wave velocity (P-wave velocity, V_p) was calculated by following equations;

$$V_p = \sqrt{\frac{K + {}^4/_3\, \mu}{d}}$$

where d denotes density, K and μ is bulk modulus and shear modulus which were estimated from stress-strain relationship with engineering triaxial stress by FEM. Electrical resistivity simulation applies 30 mV of electrical field in z-direction (same as fluid-flow direction) and calculates electric current. From this applied voltage (V) and calculated electric current (I), resistivity (ρ) can be calculated as;

$$\rho = \frac{\mathrm{V}}{I}\frac{\pi D^2}{4L}$$

where D and L is diameter and length of the sample, respectively. Detailed simulation input parameters are summarized in Table1.

Table 1. Input parameters of numerical simulation by FEM

Parameters	Rock	Fluid
Conductivity [S/m]	0.001	1.75
Bulk modulus [GPa]	34	2.2
Shear modulus [GPa]	35	0
Density [kg/m^3]	2900	997

2.3 Experimental validation

Fluid-flow tests were performed under confining pressure ranging between 6 and 20 MPa. Pore pressures of upstream and downstream were fixed as 5 and 4 MPa, respectively. During the test, flow rate (Q) was monitored by a digital logger and thereby permeability (k) is calculated by following equation (Darcy's law),

$$\frac{Q}{A} = \frac{k}{\mu}\frac{dp}{dx}$$

while A, μ and dp/dx is cross sectional area, viscosity and pressure gradient, respectively. Consequently, from this calculated permeability, we estimated fracture permeability (k_f) as follows [22];

$$k_f = \frac{e^2}{12}$$

where hydraulic aperture (e) is written by

$$e^3 = \frac{12\mu Q}{D}\frac{dx}{dp}$$

while D is the width of fracture.

During this fluid-flow experiment, electrical resistivity and elastic wave velocity were simultaneously measured by using four electrodes-method and pulse transmission method, respectively [23]. These measured permeability, resistivity and velocity were compared with calculated results for the validation of simulation results.

3. RESULTS AND DISCUSSION

Fig. 1 shows hydraulic permeability, electrical resistivity and elastic wave velocity of both of experimental and simulated results as a function of effective confining

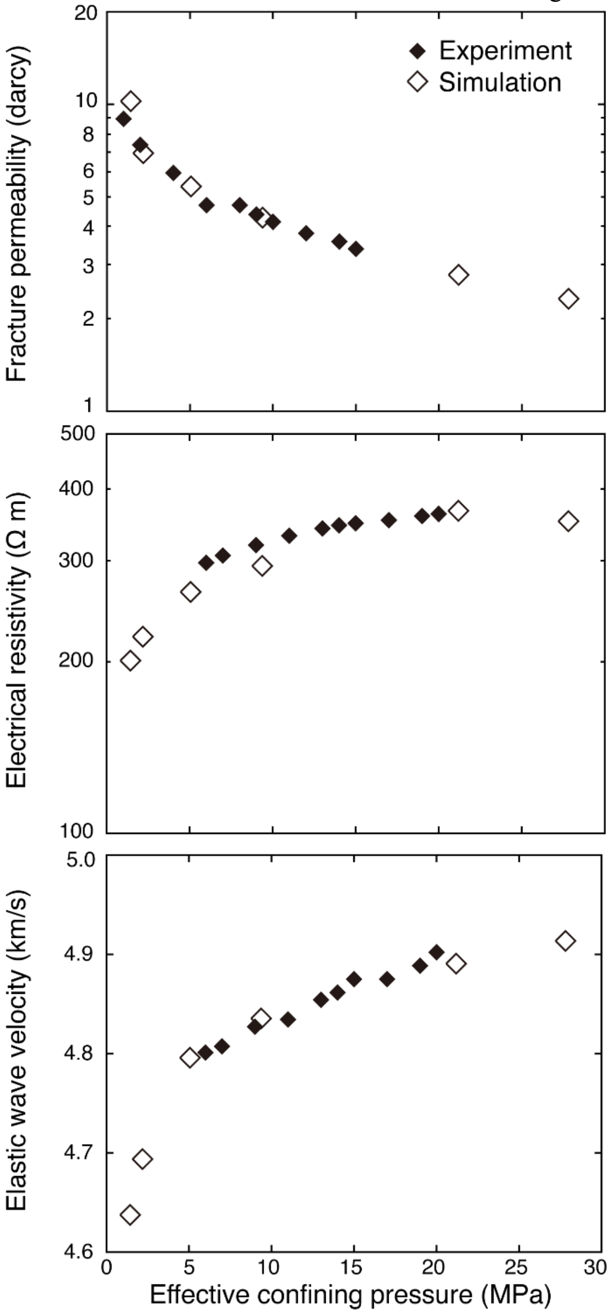

Fig. 1. Changes of hydraulic permeability, electrical resistivity and elastic wave velocity against the effective confining pressure. Note that pressure condition of

numerical simulation was estimated by using aperture-pressure relationship based on permeability matching approach.
pressure. Although simulated results originally calculated these parameters as a function of mean aperture, effective confining pressure was estimated in each aperture condition from aperture-pressure relationship based on the permeability matching approach [4, 5]. Despite the fact that only permeability was used for the matching, calculated resistivity and velocity also show good agreements with experimental results. Furthermore, the threshold of resistivity and velocity changes appeared at ~5 MPa of effective confining pressure.
For further investigation of resistivity and velocity changes with aperture closure, these properties are plotted against the mean aperture of fracture (Fig. 2). Mean aperture values during the experiment were estimated from aperture-pressure relationship at each pressure condition. Whereas both resistivity and velocity decrease with increasing mean aperture, the decreasing rate of them becomes different after ~0.8 mm of mean aperture. This ~0.8 mm of aperture condition is consistent with ~5 MPa of effective confining pressure where resistivity and velocity show thresholds. In addition to these thresholds, fluid pathway is disconnected after this pressure condition. In other words, connective fluid pathway may be formed at ~0.8 mm of aperture condition. Once connective fluid pathway is formed, resistivity may not change while velocity shows continuous changes against the aperture opening. This suggests that velocity has higher sensitivity against the aperture opening whereas resistivity can be useful for detecting connection or disconnection of fluid pathways with aperture changes.

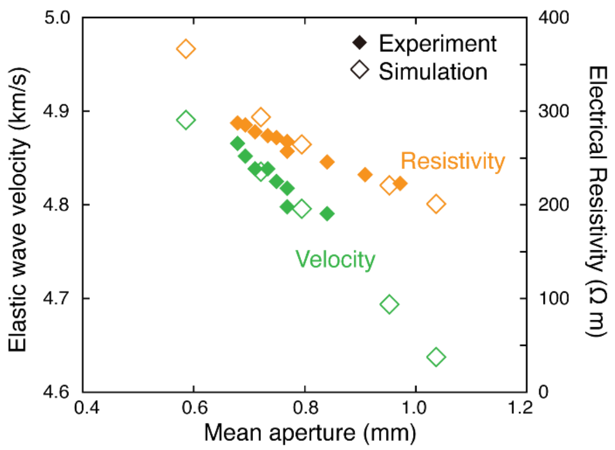

Fig. 2. Elastic wave velocity and electrical resistivity changes as a function of mean aperture. Note that mean aperture during the experiment was estimated by using aperture-pressure relationship based on permeability matching approach.

4. CONCLUSSION

The present study developed experimentally-validated numerical approach that can simultaneously investigate hydraulic permeability, electrical resistivity and elastic wave velocity from the digital image of natural rock fracture. From the permeability matching approach, we estimated mean aperture during the experiment and also pressure condition in each numerical simulation which could not be determined by only the experiment or simulation. As a result, resistivity and velocity shows threshold at the same pressure condition (~5 MPa in our study) while decreasing rates of them with aperture opening would be different after 0.8 mm of aperture condition (decreasing rate of resistivity is ~60 Ωm while that of velocity is ~80 m/s per 0.1 mm aperture change). These behaviors may be controlled by connection or disconnection of the fluid pathway which was observed by Lattice Boltzmann fluid-flow simulation. Our new approach can reveal the resistivity and velocity changes with aperture closure or opening and our results suggest that resistivity monitoring can be useful for detecting connection or disconnection of the fluid pathway while aperture opening can be monitored by velocity measurement.

5. REFERENCES

[1] R. H. Sibson, Earthquake rupturing as a mineralizing agent in hydrothermal systems, Geology, 15 (1987) 701–704.
[2] A. J. Hawkins, M. W. Becker, J. W. Tester, Inert and adsorptive tracer tests for field measurement of low-wetted surface area. Water Resour. Res., 54 (2018) 53415–5358.
[3] E. R. Okoroafor, R. N. Horne, The Impact of Fracture Roughness on the Thermal Performance of Enhanced Geothermal Systems, GRC Transactions, 42 (2019).
[4] N. Watanabe, N. Hirano, N. Tsuchiya, Determination of aperture structure and fluid flow in a rock fracture by high resolution numerical modeling on the basis of a flow-through experiment under confining pressure, Water Resour. Res., 44 (2008).
[5] T. Ishibashi, N. Watanabe, N. Hirano, A. Okamoto, N. Tsuchiya, Beyond-laboratory-scale prediction for channeling flows through subsurface rock fractures with heterogeneous aperture distributions revealed by laboratory evaluation, J. Geophys. Res. Solid Earth, 120 (2015) 106–124.
[6] T. Taira, N. Avinash, F. Brenguier, M. Manga, Monitoring reservoir response to earthquakes and fluid extraction, salton sea geothermal field, California. Science Advances, 4 (2018).
[7] J. R. Peacock, S. Thiel, P. Reid, G. Heinson, Magnetotelluric monitoring of a fluid injection: Example from an enhanced geothermal system. Geophysical Research Letters, 39 (2012), 3–7.
[8] W. F. Brace, A. S., Orange, T. R. Madden, The effect of pressure on the electrical resistivity of water-saturated crystalline rocks. J. Geophys. Res., 70 (1965), 5669–5678.
[9] A. Nur, G. Simmons, The effect of saturation on velocity in low porosity rocks. Earth and Planetary Science Letters, 7 (1969), 183–193.
[10] A. Revil, N. Florsch, Determination of permeability from spectral induced polarization in granular media, Geophysical Journal International, 181(2010), 1480–1498.
[11] K. Zaima, I. Katayama, Evolution of Elastic Wave Velocities and Amplitudes During Triaxial Deformation of Aji Granite Under Dry and Water‐Saturated Conditions. J. Geophys. Res. Solid Earth, 123 (2018), 9601-9614.

[12] T. Watanabe, A. Higuchi, Simultaneous measurements of elastic wave velocities and electrical conductivity in a brine-saturated granitic rock under confining pressures and their implication for interpretation of geophysical observations, Progress in Earth and Planetary Science, 37 (2015).
[13] Guéguen, Y., and Palciauskas, V. Introduction to the physics of rocks, Princeton, New Jersey, 1994, 294p.
[14] G. Mavko, T. Mukerji, J. Dvorkin, The Rock Physics Handbook: Tools for Seismic Analysis of Porous Media. Cambridge University Press, Cambridge, 2009, 511p.
[15] A. Kirkby, G. Heinson, L. Krieger, Relating permeability and electrical resistivity in fractures using random resistor network models, J. Geophys. Res. Solid Earth, 121 (2016).
[16] L. J. Pyrak-Nolte, D. D. Nolte, Approaching a universal scaling relationship between fracture stiffness and fluid flow. Nat. Commun. 7 (2016).
[17] K. Sawayama, K. Kitamura, Y. Fujimitsu, Laboratory measurements on electric and elastic properties of fractured geothermal reservoir rocks under simulated EGS conditions. GRC Transactions, 42 (2018) 2459–2475.
[18] F. Jiang and T. Tsuji, Changes in pore geometry and relative permeability caused by carbonate precipitation in porous media, Physical Review E 90 (2014).
[19] N. Mohd, C. Hu, X, Li, WAVE-STRUCTURE INTERACTION USING FREE SURFACE LATTICE BOLTZMANN METHOD (FSLBM), IEICES (2015) 11–12.
[20] N. A. C. Sidek, A. A. Kihan, Experimental and Numerical Simulation Investigation of Flow Over a Cavity Using Multi- Relaxation Time Lattice Boltzmann Method, IEICES (2016) 45–48.
[21] E, J. Garboczi, Finite Element and Finite Difference Programs for Computing the Linear Electric and Elastic Properties of Digital Images of Random Materials (1998).
[22] P. A. Witherspoon, J. S. Y. Wang, K. Iwai, J. E. Gale, Validity of cubic law for fluid flow in a deformable rock fracture, Water Resour. Res., 16 (1980).
[23] K. Sawayama, K. Kitamura, Y. Fujimitsu, Relationship between Complex Resistivity, Elastic Wave and Water Saturation of Cracked Andesite under Laboratory Fluid-Flow Test. BUTSURI-TANSA (Exploration Geophysics), 71 (2018) 71–85.