Permeability Estimation of Crack Type and Granular Type of Pore Space in a Geothermal Reservoir Using Lattice Boltzmann Method and Kozeny-Carman Relation

Almira Anissofira, and Fourier D. E. Latief

Physics of Complex Systems, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jalan Ganesha 10 Bandung 40132, West Java, Indonesia

almiraanissofira@gmail.com, fourier@fi.itb.ac.id

Keywords: permeability, Lattice Boltzmann method, Kozeny-Carman relation, crack type, pore type, geothermal

ABSTRACT

Permeability is one of the key rock properties for the parameter in geothermal reservoir management. Permeability is highly dependent to other petrophysical parameters such as porosity, specific surface area, and tortuosity. Geothermal rocks generally contain crack type and granular type of pore space which allow flow of various kinds of fluids, including steam in geothermal reservoirs. Pore space with high permeability indicates the ability to easily transport the fluid. This study aims to compare two methods of estimating permeability of crack type and granular type of pore space in geothermal reservoir to later discuss which type of pore plays more important role in transporting fluids. We used Lattice Boltzmann Method and Kozeny-Carman relation to estimate permeability. From these analyses, permeability values of crack type and granular type obtained by Lattice Boltzmann are 141,490 mD and 148 mD respectively, and then by Kozeny-Carman are 273,669 mD and 26,858 mD respectively. From both methods, it had been shown that the crack type has a predominant role to transporting fluid in the geothermal reservoir compared to the granular type. Kozeny-Carman relation is considered to be less accurate, because this method is usually more valid for the case of sandstone. Kozeny-Carman relation is direction independent, and is also highly influenced by the method of calculating the quantities in the equation, which are porosity, specific surface area, the Kozeny constant (geometrical factor) and tortuosity. Lattice Boltzmann Method is considered to be more accurate than Kozeny-Carman relation, since it simulates the fluid transport through the pore space. Permeability estimated by Lattice Boltzmann method is direction dependent, thus can be used to further calculate the permeability anisotropy. Equivalent permeability which calculated using arithmetic averaging yield better results in estimating the undivided original sample which contains both types of pore space.

1. INTRODUCTION

Permeability is one of the key petrophysical parameters for managing sub-surface energy resources including hydrocarbon and geothermal reservoirs as well as aquifers. Permeability is often defined as a measure of how easily fluid moves through rock, which is related to the connectedness of the void spaces inside the porous rock. A rock could be extremely porous, but if each pore was isolated from the others, the rock would be considered impermeable. Some volcanic rocks have many vesicles, but the vesicles are isolated, rendering the rock impermeable (Bennington, 2010). Various research studies regarding permeability of geothermal reservoir system have been conducted. Bardsley et al (2012) describes that identifying permeable zones is essential for economically viable exploration and development of conventional geothermal reservoirs with natural high permeability, thus it is important to controls hydrothermal fluid flow in a geothermal production field. Dou et al (2014) recently developed a mathematical model for describing the heat energy extracted from a hot dry rock in a multi-well system and concluded that the effective permeability enhancement (due to hydraulic stimulation) is found almost proportional to the density of the reservoir natural fractures. Permeability k is a function of properties of the pore space, such as porosity ϕ and several other structural parameters (Pape et al., 1998). The study regarding permeability is also thought-provoking in the cases where the pore fluid is multiphase, because there is still an immense uncertainty in terms of permeability equation of multiphase fluid flow through porous and fractured media (Habana, 2002).

This study is a development from previous works conducted by Latief et al (2012, 2014) and Anissofira et al. (2014), and the aim is to analyze the permeability of pore space in geothermal reservoir rocks. Geothermal reservoir rocks have two different kind of pore space which contribute to transporting and distributing fluids, which are the granular-type and crack-type (Faybishenko et al., 2013; Latief and Feranie, 2012). We take advantage of the digital rock physics (DRP) in which the 3D digital data (images) can be used to visualize the internal structure of the porous rock: both the matrix structure and the pore structure. From many points of view, DRP provides faster, better, and lower-cost analysis (Rassenfoss, 2011). By applying the DRP analysis, we can perform virtual computer-based experiments which have certain advantages over the physical experiments, e.g., the former is non-destructive. A 3D pore structure that is reconstructed from very small rock drill cuttings can be reused many times in a number of numerical experiments by almost limitless methods which are widely available. By doing so, the virtual experimentalist can tremendously expand the database without using additional cores/cuttings when the DRP technique is implemented. Thus in this research we use the widely used Kozeny Carman relation and Lattice Boltzmann Method (LBM) to estimate the permeability of pore space inside the geothermal reservoir rock.

2. PERMEABILITY ESTIMATION

Single phase permeability (which is often referred as absolute permeability) of a porous medium can be estimated using various techniques. This physical parameter which is widely described as the measure of the ability of a porous material to transport a single-phase fluid has the SI unit of square meter (m^2). However, the square micrometer (μm^2) is more common in geophysics since it is almost equivalent to one darcy (D): $1\ D = 0.987 \times 10^{-12}\ m^2$. One darcy is the permeability of a sample that has a length of 1 cm and has a cross-section area of 1 cm^2, where the difference pressure between the ends of the sample is set at 1 dyne/cm2, the

dynamic viscosity of the fluid is 1 poise flowing at a rate of 1 cm^3/s. In the application of geology, the unit darcy is too large, so a smaller unit is used, that is millidarcy (mD), where 1000 mD = 1 D (Haq, 2012).

Kozeny-Carman equation and LBM are applied to estimate the permeability of pore space inside the geothermal reservoir rock: the segmented crack-type and granular-type of pore space, as well as the whole pore space (unsegmented). Kozeny-Carman equation is applied by taking several assumptions regarding the pore structure, while LBM simulates viscous fluid flow through pore space using the same concept which is applied when using the Darcy's law.

2.1 Kozeny-Carman Relation

Most non-empirical models are based on the Kozeny-Carman relation (Carman, 1937), which links permeability to the effective pore radius. We have applied Kozeny-Carman relation in order to obtain the value of permeability. The Kozeny-Carman relation is expressed as follows (Dvorkin, 2009):

$$K_{abs} = \frac{1}{K_c} \frac{\phi^3}{S_D^2 \tau^2} \tag{1}$$

where K_{abs} is absolute permeability value of porous medium (unit: m^2); K_c is a general constant (sometimes related to pore geometry); ϕ is fraction volume of pore space (dimensionless); S_D is total surface area of the porous medium (unit: m^2); and τ is tortuosity. In some cases, due to the limitation of calculating tortuosity, this property is assumed to have the value in the range of 1.5 – 2.5, depends on the complexity of the pore structure, which in most cases are quite difficult to estimate. In this study, the porosity can be calculated easily by dividing the amount of voxels from the 3D image which correspond to void by the amount of total number of voxels of the whole digital sample. The total surface area is calculated as ratio between the area of the pore wall to the volume of the sample, in which we use edge detection to label the pore wall. Assuming the pore shape can be treated as cylindrical tube, we use $K_C = 2$, while the tortuosity is calculated from the ratio of tortuous path to the side-by-side length of the sample in the z-direction

2.2 Lattice - Boltzmann Simulation

LBM is considered one of the most widely and rapidly developed DRP analysis based on statistical description of fluid flow phenomenon. LBM describes fluid flow as collisions of imaginary particles that are much bigger than fluid molecules. The collision rule preserves mass and momentum and is implemented on a 3D lattice superimposed onto a realistic pore space (Dvorkin. et al, 2003). The basic concept of permeability is closely associated with the law of fluid flow through porous media and is known as Darcy's law. Darcy equation can be written as follows:

$$\frac{Q}{A} = - \frac{k}{\mu} \frac{P_i - P_0}{L} \tag{2}$$

where Q is flow rate of fluid transported through the pore space (units cm^3 s^{-1} or m^3 s^{-1}); P_0 for the fluid pressure at the outlet (units dynes cm^{-2} or Pa); P_i = fluid pressure at the inlet (dynes cm^{-2} or Pa); μ = dynamic viscosity of fluid (poise or Pa.s); L = length of the medium (cm or m); k = permeability of the sample (darcy or m^2); A = cross sectional area of sample (cm^2 or m^2). We use Parallel Lattice Boltzmann Solver (Palabos, www.palabos.org) to conduct the fluid flow simulation where we applied the D3Q19 scheme. From the simulation, the permeability can be calculated using the following equation in order to conform to Palabos:

$$k = \frac{\langle v \rangle}{dP / dL} \tag{3}$$

2.3 Equivalent permeability

Equivalent permeability is often used in cases where the porous medium is considered heterogeneous. It shows how equivalence is defined by using a criterion of flow or energy dissipated by viscous forces and explains the two different concepts of effective permeability and block permeability (Renard, 1997). We use the following equations to calculate equivalent permeability (Fauzi et al., 2012):

2.3.1 Arithmetic Averaging

$$\overline{k_A} = \frac{\sum_{i=0}^{n} k_i}{n} \tag{3}$$

2.3.2 Geometrical Averaging

$$\overline{k_G} = \sqrt[n]{k_1 k_2 k_3 \ldots\ldots k_n} \text{ , and} \tag{4}$$

2.3.3 Harmonic Averaging

$$\overline{k}_n = \frac{n}{\left(\sum_{i=0}^{n} \frac{1}{k_i}\right)} \tag{5}$$

For all the three equations, $n = 2$ where $k_1 = k_C$ (permeability of crack-type of pore space) and $k_2 = k_g$ (permeability of granular-type of pore space). The equivalent permeability is used to estimate the permeability of the whole (unsegmented) sample.

3. DATA

The sample used in this research is a geothermal rock from West Java, Indonesia (Figure 1, top row). By using a µCT scanning device, the digital data from the rock was obtained to later generate a three-dimensional image of the rock itself. The sample was obtained from the depth around 500 m below the surface, and has spatial dimensions of 3 cm × 3 cm × 5 cm. We can visually observe that the sample has cracks that are highly visible and by digitizing the sample, the internal structure can be further analyzed.

3.1 Digital Reconstruction

The digital images of the rock were produced by using SkyScan 1173 µCT scanner (Figure 1, bottom). This device is specialized to produce high energy X-Ray which is suitable to scan such high density rock. The scanning parameters are listed in Table 1. Using NRecon, a software to reconstruct the images based on the Feldkamp algorithm, the cross-sectional images are then produced (Figure 2). As we can see in Figure 2, by manipulating the color spectrum (which basically describes the pseudo-density of the materials) we can enhance the visibility of the pore space, especially the crack-type.
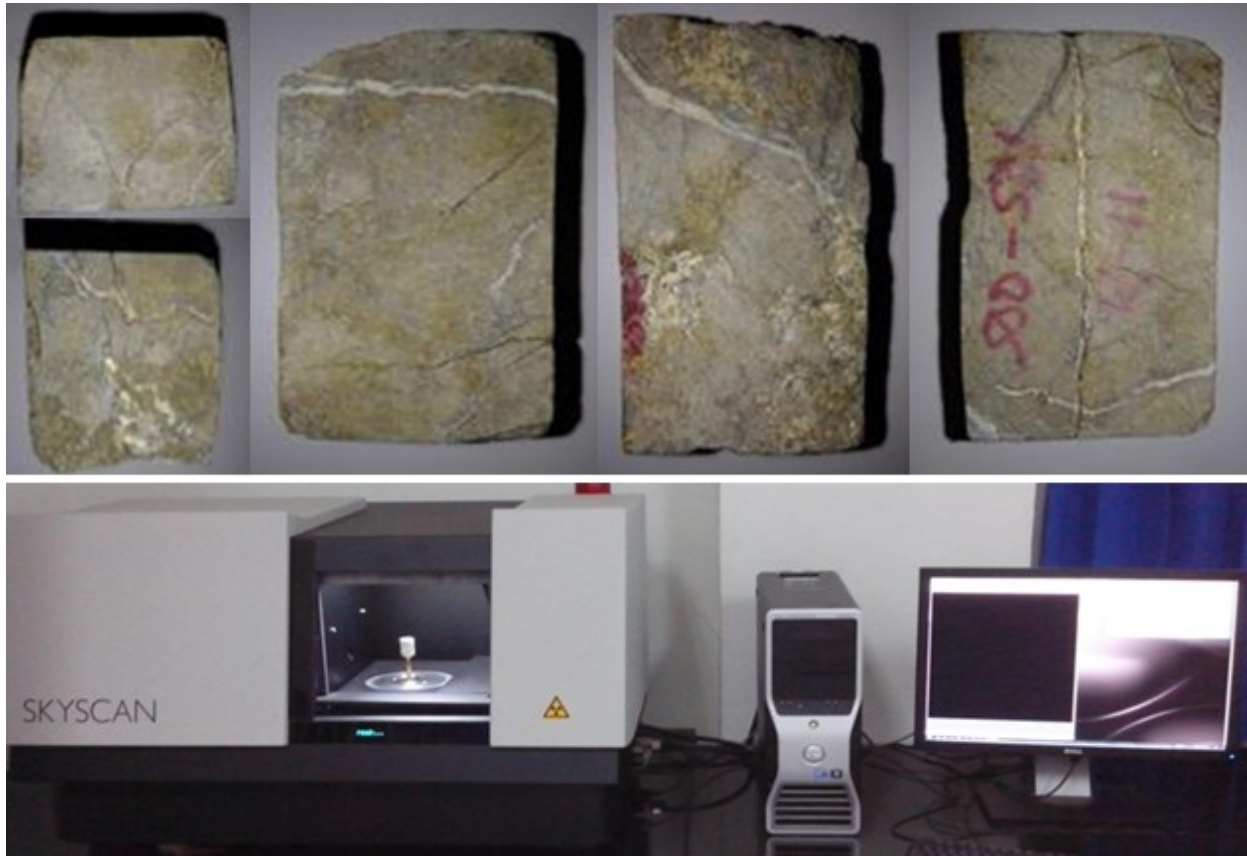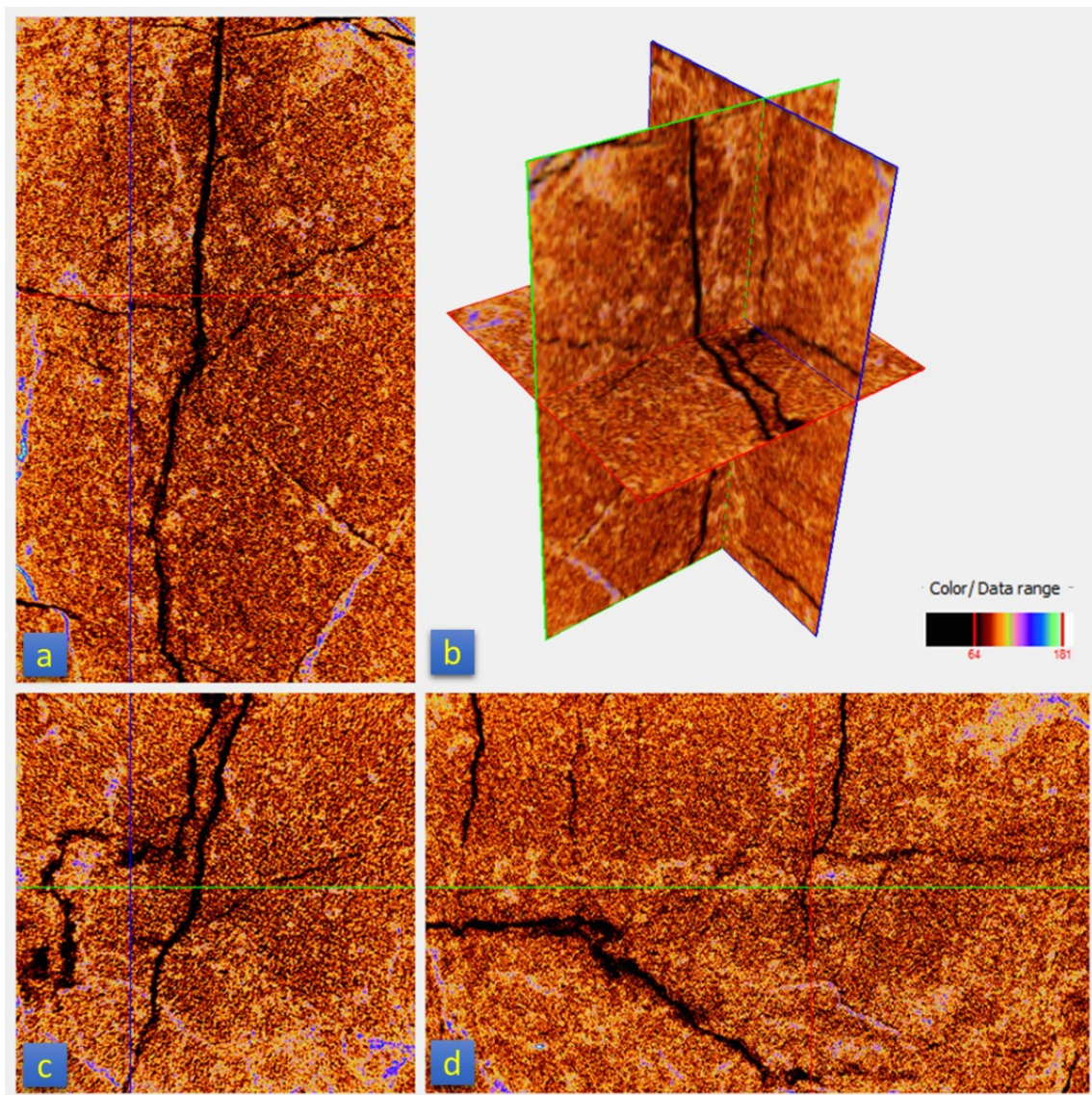

Figure 1: Top: the geothermal reservoir rock sample, view from left to right: top-bottom, front, left, and right. Bottom: µCT scanning device SkyScan 1173.

3.2 Pore Space Segmentation and Visualization

In order to calculate the petrophysical properties which are volume fraction of pore space and specific surface area, we first need to separate between the crack-type and granular-type. Visualization is substantially important in terms of analyzing the sample qualitatively. Visualization of the digital sample was performed using ImageViewer and CTVox (www.skyscan.be). Two dimensional qualitative analysis can be done using ImageViewer as shown in Figure 2. The color visualize the pseudo-density of the rock sample. The scale of the color is adjusted such that the cracks have high visibility. By using images in Figure 2, we can observe that the cracks have better connectivity in the *z*-direction compared to other direction. Small branches are also visible, however it cannot yet be concluded how significantly these branches contribute to the fluid flow (Anissofira, 2014).

Table 1. Scanning parameter for rock's sample (Latief et al., 2014)

Scanner	SkyScan 1173
Sample spatial dimension	3 cm × 3 cm × 5 cm
Voltage	130 KV
Exposure time	295 ms
Rotation step	0.4°
Filter	0.25 mm brass
Camera binning	2 × 2 (1120 × 1120 pix)
Object-source distance	218.412 mm
Camera-source distance	364.000 mm
Image resolution	59.85 μm (isotropic)
Scanning interval	15 min 14 sec
Number of raw projection images	600 (TIFF images)
VOI	440×440×730

Figure 2: Color-coded pseudo-density 2D slice view. (a) Coronal image, sliced at *x* = 125 (b) Ortho-slice view (c) Transaxial image, sliced at *z* = 425 (d) Sagittal image, sliced at *y* = 225.

A more enhanced three dimensional visualization can be performed using CTVox (see Figure 3). The color of certain region can be further modified by modifying the RGB transfer function. Although we cannot clearly observe the nature of the connectivity of the crack from the orthogonal view of Figure 3, by rotating the images in CTVox, we can conduct qualitative analysis on each type.
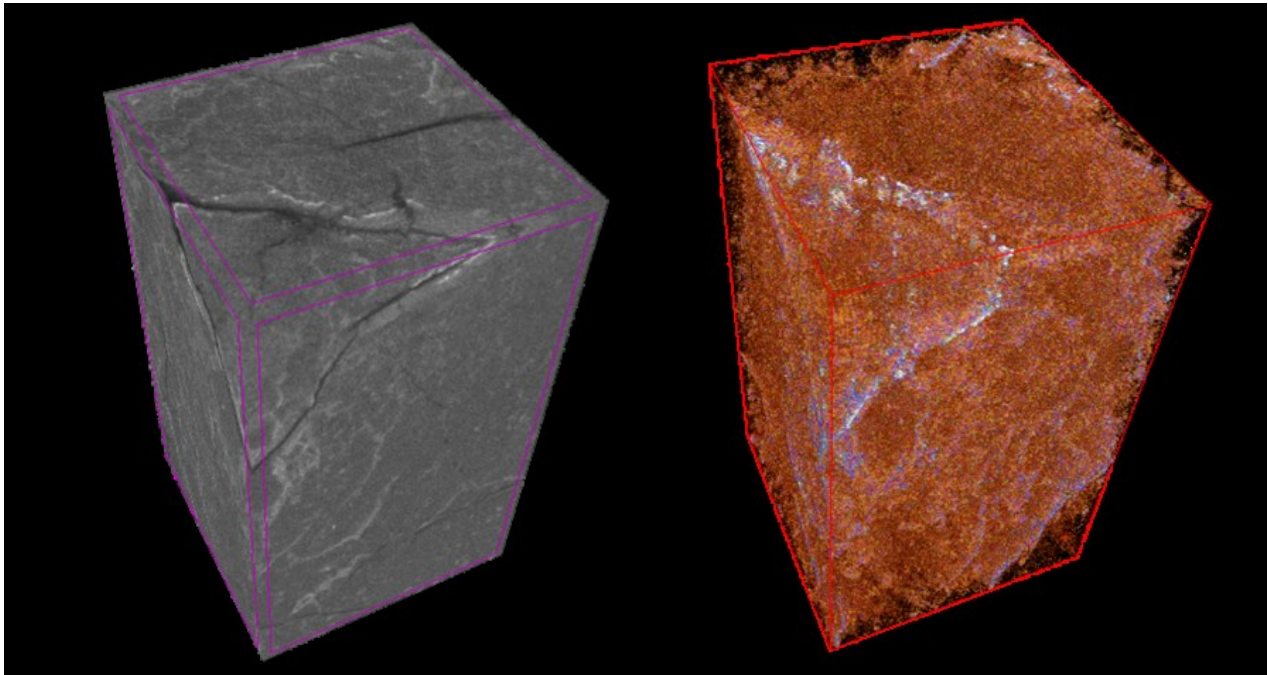

Figure 3: 3D visual of the digitized sample. Left: original grayscale reconstructed image. Right: visually enhanced pseudo-density color of the digitized sample.

Subsequent to obtaining binary images of crack type and granular type of pore space, calculation of permeability can then be done. The corresponding 2D and 3D visual of the unsegmented pore space, crack-type pore space and granular-type of pore space can be seen in Figure 4. Various characterizations can be conducted on the geothermal rock by using image processing post to digital reconstruction of 3D pore space from 2D images and the pore space segmentation. Estimating permeability with the Kozeny-Carman relation and also the Lattice-Boltzmann fluid flow simulation can then be done. Kozeny-Carman relation can be applied by first calculating the required parameters i.e., volume fraction of crack-type of pore space, volume fraction of granular-type of pore space, surface density, and permeability (Latief and Feranie, 2012). Total porosity is the total pore volume per unit volume of rock. Volume fraction of pore space and the crack (crack porosity) can be calculated using the 3D binary image (Figure 4 a,b,c). The second property is the surface density, property of solids which is the total surface area of a material to the total volume of the sample (Dvorkin, 2009). The third property is tortuosity, in terms of flow properties, tortuosity can also be defined as ratio between the magnitude of velocity vector in certain direction to the norm velocity. The value of tortuosity can generally describe the trajectory of the fluid inside the pore space. In general, the value of the tortuosity could be 1 or more than 1 which represent how curved the trajectory is (Koponen et al., 1996).

4. RESULT

Table 2 lists all the calculated parameters. The volume fraction of the pore space of the granular type is larger than the crack-type, the permeability of the granular-type is much less smaller. However, this does not always mean the granular type has greater permeability value than crack type. The fact that the surface density of the granular-type is greater than the crack-type can roughly be interpreted as the pore structure of the granular pore type being more complex. This is confirmed by the result of permeability estimation by both of Kozeny Carman relation and Lattice Boltzmann simulation. The difference of the permeability between the crack type and the granular type of pore space are very significant. For the value of tortuosity has correlation with average velocity of the sample. The results from the tortuosity calculation can also be used in explaining the tendency of the permeability. Higher tortuosity can be related with a more twisted (tortuous) trajectory of the fluid flow than the lower tortuosity. The average velocity of the fluid flow inside the crack-type of pore space is higher, which can also be roughly related to a trajectory more likely to be straight. The contrast of values of permeability between the crack-type and the granular-type clearly describes that for the crack-type is more likely to be easier to transport the fluid. Table 3 lists the equivalent permeability calculated using three different equations.

By implementing arithmetical, geometrical and harmonic averaging on the permeability from each method (the Kozeny-Carman relation and LBM), the value of equivalent permeability can be calculated. The equivalent permeability is used to predict the permeability of the whole (original unsegmented) sample. By analyzing the result, arithmetic averaging is considered the more suitable approach since it yields more similar value of the permeability for both methods (Kozeny-Carman and LBM).
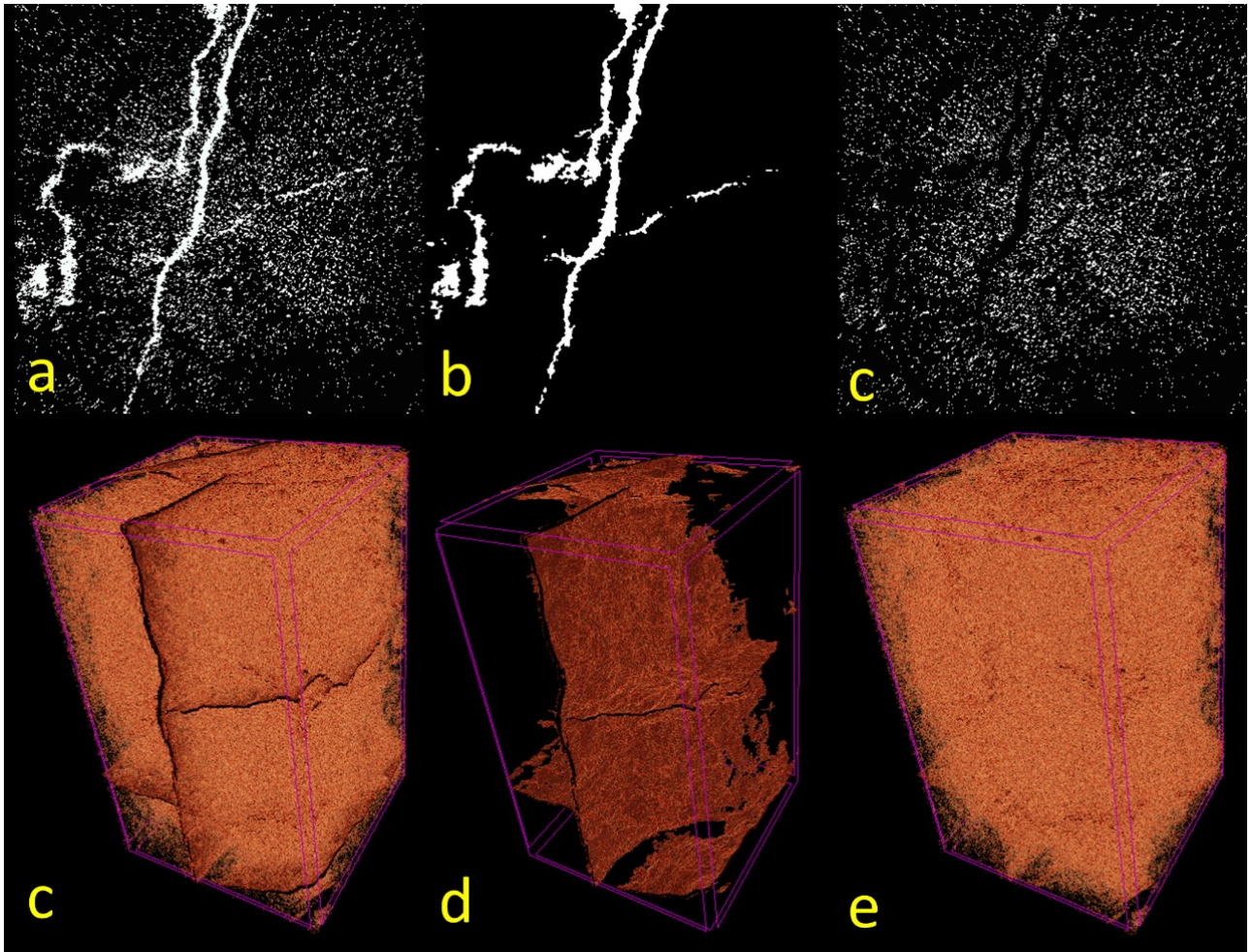
Figure 4: Top row: Binary image which contains granular-type and crack-type of pore space. Middle row: Binary image which contains cracks only. Bottom row: Binary image which contains granular only.

Table 2: Characteristics of pore space of the geothermal rock's samples.

Characteristics	Original Sample	Crack	Granular
Volume Fraction (%)	8.24	2.74	5.86
Surface Density (1/lu)	7.08	1.06	5.84
Average velocity	7.55231×10^{-9}	1.60422×10^{-8}	1.67721×10^{-11}
Lattice viscosity	0.166667	0.166667	0.166667
Pressure Gradient	6.85871×10^{-8}	6.85871×10^{-8}	6.85871×10^{-8}
Tortuosity	1.1524	1.0975	2.3309
Permeability (by Kozeny-Carman Relation) (mD)	152,522	275,839	19,708
Permeability (by Lattice Boltzmann Method) (mD)	66,610	141,490	148

Table 3: Equivalent permeability estimation of pore space of the geothermal rock's samples.

Method	Arithmetical	Geometrical	Harmonic
Kozeny-Carman Relation (mD)	147,774	73,731	36,788
Lattice Boltzmann (mD)	70,819	4,575	296

As an addition to the analyses performed above, streamlines of fluid trajectory can be generated by using Paraview. The streamlines were generated by carrying out integration of the velocity vectors using Interpolator with Point Locator in both forward and backward direction of Runge-Kutta 4-5 integrator type. The darker regions show lower velocity. The visual shows that for the granular type of pore space, the streamlines are mostly poorly connected resulting in very low velocity vectors. On the contrary, the flow inside crack-type produces higher velocity vectors, and as we can observe clearly, are mostly well connected.
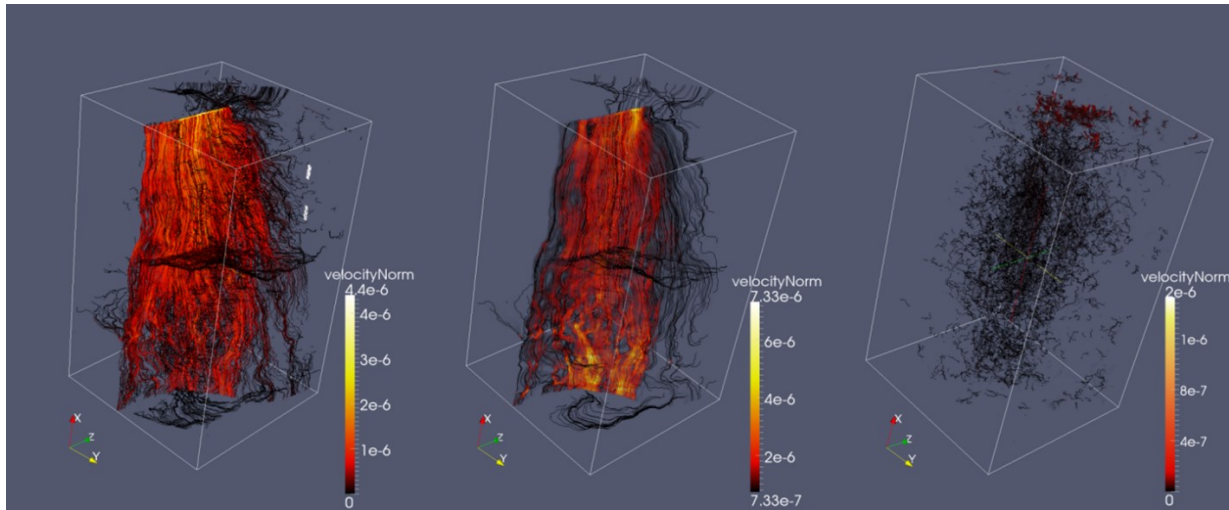

Figure 5: Velocity profile produced by simulating fluid flow using Palabos. From left to right: contains cracks and granular type of pore space, contains crack type of pore space only, and contains granular type of pore space only.

5. CONCLUSION

Higher value of pore volume fraction does not always means that the permeability is higher. Despite the fact that the volume fraction of crack is only 2.74 % and the volume fraction of the granular type is 5.86%, permeability of crack type and granular type obtained by Lattice Boltzmann are 141,490 mD and 148 mD respectively, and by Kozeny-Carman are 273,669 mD and 26,858 mD respectively. From both of the methods, it had been shown that the crack type has a more significant role in transporting fluids in the geothermal reservoir compared to the granular type. Kozeny-Carman relation is considered to be less accurate, because this method is usually more valid for the case of sandstone. Kozeny-Carman relation is direction independent, and is also highly influenced by the method of calculating the quantities in the equation, which are the porosity, specific surface area, the Kozeny constant (geometrical factor) and tortuosity. Lattice Boltzmann Method is considered to be more accurate then Kozeny-Carman relation, since it simulates the fluid transport through the pore space. Permeability estimated by Lattice Boltzmann method is direction dependent, thus can be used to further calculate the permeability anisotropy. Equivalent permeability calculated using arithmetic averaging yield better results in estimating the unsegmented original sample which contains both types of pore space.

REFERENCES

A. Koponen., M. Kataja., and J. Timonen.: Tortuous Flow in Porous Media, Physical Review E,54 (1), (1996), pp 406-410.

Anissofira, A., Latief, F. D. E., and Widijana, A. R. T.: Tortuosity And Permeability Analysis Of Crack Type And Granular Type Of Pore Space In A Geothermal Reservoir Rock, *Proceedings*, 3rd International ITB Geothermal Workshop 2014 Institut Teknologi Bandung, Bandung, Indonesia, (2014).

Bardsley, C., Sewell, S., Cumming, W. B., Minnick, M.; Rowland, J. V., O'Brien, J., and Price, L.: Controls on Hydrothermal Fluid Flow Within the Rotokawa Geothermal Field, New Zealand: Insights from 3D Geological Models, American Geophysical Union, Fall Meeting (2012), abstract #V13A-2820

Bosl, W., Dvorkin, J., and Nur, A.: Lattice- Boltzmann Simulation of Permeability in Granular Rocks, SEG Technical Program Expanded Abstracts, (1997): pp. 999-1000.

Carman, P.C., Fluid flow through granular beds, Transactions of the Institute of Chemical Engineering (1937) 15:150–66.

Dou, B., Gao, H., Zhou, G., Ren, L.: Numerical Simulation of Heat Transfer from Hot Dry Rock to Water Flowing Through a Circulation Fracture (Conference Paper), 3rd International Conference on Materials Science and Engineering, ICMSE 2014; Jiujiang; China; 24 January 2014 through 26 January 2014; Code 102768, Advanced Materials Research, Volume 852, (2014), Pages 831-834.

Dvorkin, J., Kozeny-Carman Equation Revisited, (2009).

Dvorkin, J., Walls, J., Tutuncu, A., Prasada, M., Nur, A., and Mese, A.: Rock Property Determination Using Digital Rock Physics, SEG Technical Program Expanded Abstracts 2003, (2003): pp. 1660-1663.

Faybishenko, B., Witherspoon, P. A., and Bodvarsson, G. S.: Emerging Issues in Fractured-Rock Flow and Transport Investigations: Introduction and Overview, Lawrence Berkeley National Laboratory, Berkeley, California, USA (2013).

Fauzi, U., Annisa., and Latief, F.D.E.: Effective Permeability of Layering Simple Grain Packings, *Proceedings*, 37th HAGI Annual Convention and Exhibition, Palembang, (2012).

Ganguly, S., and Kumar, M. S. M. : Geothermal Reservoirs – A Brief Review, *Journal Geological Society of India (JGSI)*, Vol. 79, (2012), pp 589-602.

Habana, M.D.: Relative Permeability of Fractured Rock, SGP-TR-172, Stanford Geothermal Program Interdisciplinary Research in Engineering and Earth Sciences Stanford University Stanford, California (2002).

Haq, T.M.: Rekonstruksi Dan Simulasi Digital Untuk Menentukan Karakter Fisis Dari Reservoir Batupasir. Undergraduate Final Project Report, Program Studi Teknik Geofisika Fakultas Teknik Pertambangan Dan Perminyakan Institut Teknologi Bandung (2012).

Keehm, Y., Mukerji, T., Prasad, M., and Nur, A.: Permeability Prediction from Thin Sections Using the Lattice- Boltzmann Flow Simulation, SEG Technical Program Expanded Abstracts 2003, (2003), pp. 1668-1671.

Latief, F.D.E., Umar, F., and Feranie, S.: Digital Isolation Teqnique for Reconstruction and Visualization of Cracks in Micro-CT Images of Geothermal Reservoir Rock – Microscopy and Analysis 28 (2), (2014), 12 – 15 (AP).

Latief, F.D.E., and Feranie, S.: Three-Dimensional Visualization and Characterization of Cracks in Geothermal Reservoir Rock Using Image Analysis of Reconstructed μCT Images: A Preliminary Study, The Fourth International Conference on Mathematics and Natural Sciences (ICMNS 2012), Bandung, Indonesia (2012).

Pape, H., Clauser, C., and Iffland, J.: Permeability prediction for reservoir sandstones and basement rocks based on fractal pore space geometry. SEG Technical Program Expanded Abstracts 1998, (1998), pp. 1032-1035.

Renard Ph.: Calculating equivalent permeability: a review, *Advances in Water Resources* Vol. 20(5–6), (1997), pp. 253–278.