The effect of uniaxial pressure on development on 3D fracture and its properties of clay cap rock on one potential geothermal area in Candi Umbul-Telomoyo, Semarang-Indonesia

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Abstract. A Sample of clay cap rock on geothermal area in Candi Umbul-Telomoyo, Semarang has been digitized to the observe 3D fracture development due to the influence of uniaxial pressure. The 3D fractures were analysed using digital image processing and analysis method. The sample is an altered cases andesite breccia with diameter of 4.4 cm and height of 4.3 cm. The rock sample was collected from well at 590 m. The rock sample was given uniaxial pressure treatment of 59 bar, 75 bar, 91 bar, 107 bar, 123 bar and 156 bar. The results show that 3D fracture develops as pressure increase are total orientation $\theta(P)$, aperture $e(P)$, fracture density $\Phi(P)$, fracture intensity $I(P)$ and fractal dimension $D(P)$. Total orientation and fracture intensity have polynomial to relative to the given pressure. Aperture and fractal dimension are linearly proportional to the give pressure, while the fracture density is exponentially proportional to the give pressure. The effect of increasing pressure to the safety of this geothermal clay cap was studied by conducting a continuous uniaxial compressive test on the sample. From this test, it is observed that the sample broken at the pressure of 478 bar.

1. Introduction
The geothermal area of the Candi Umbul-Telomoyo is very interesting because of the emergence of geothermal manifestations thought to be associated with the activity of the Telomoyo volcano in the volcanic geological environment in the quarter. The clay cap of thick andesite lava has a low permeability and becomes a good clay cap for the geothermal system of Candi Umbul-Telomoyo [1]. The clay cap properties that are impermeable and have low permeability can be explained by the presence of fractures contained within the clay cap rock. Fractured rock plays important role in fluid transport because it affects the permeability of rocks. The permeability of the rock serves as the fluid passage to the surface indicated by the presence of geothermal manifestation [2]. Low permeability of rocks can be overcome by treatment of rocks, including hydraulic fracturing [3], heat induced fractures [4] and chemical stimulation [5].

Hydraulic fracturing has succeeded in creating new fractures, increasing geothermal productivity. A treatment by using proppant can be done to create, a long-term conductive fractures [3]. The pressure drop in the reservoir causes a mineral enclosure and decreased permeability [6]. Many research has
been done in analysis the mechanical properties of rock due to applied stresses. Hydraulic and mechanical properties of natural fractures in low-permeability rock. The result of the effective stresses of than 20 MPa, the fluid flow was proportional to the mean fracture aperture raised to a power greater than 3. At effective stresses higher than 20 MPa, the mean fracture aperture continued to diminish with increasing stress, but this had little effect on the flow because the small tortuous flow channels were slightly deformed with the increase in tension [7]. The laboratory model gives an overview of the effect of stress either the maximum stress or the minimum stress acting on the reservoir rock and the influence of temperature and the presence of fluid on the properties of the reservoir rock strength [8]. Uniaxial compression tests have been conducted on Oshima granite under various constant axial strain rates ranging from 10⁻⁸ to 10⁻⁴. The strength and the acoustic emission rate increased exponentially with increasing strain rate [9]. However, digital rock physics are still considered to be rarely used in such analysis ever when this approach provides a mean of visualizing the structure in 3D image.

Digital Rock Physics is an analysis performed digitally without destructing the internal structures. Data in the form of digital images are obtained using Micro Computed Tomography (μ-CT) Scan [10]. This study aims to determine the effect of uniaxial pressure on the development of 3D fracture and its properties of clay cap rock on one potential geothermal area in Candi Umbul-Telomoyo, Semarang.

2. Methods
The rock sample was taken from CTL-01 thermal gradient well in the geothermal prospect area of Candi Umbul-Telomoyo located in Kemambang village, Banyubiru sub-district, Semarang regency, Central Java province (see Figure 1). The rock sample was taken at a depth of 590 m from a well with 702.60 m depth. Rock sample of cylindrical shape with a diameter of 4.4 cm and length of 4.3 cm is shown in Figure 2. The sample is an altered ceses andesite breccia which is a coreplug taken from a clay cap layer.

Figure 1. Sampling location map.  
Figure 2. Geothermal sample rock.

The Geothermal rock sample has natural pressure of 59 bar. The test use pressure of 75 bar, 91 bar, 107 bar, 123 bar and 156 bar. The pressure treatment was performed using uniaxial compressive strength testing apparatus.

This study uses the Bruker Micro CT Sky Scan 1173 [11]. This scan uses a current source of 60 μA, a voltage source of 125 kV, exposure time 300 ms and filter brass of 0.25 mm. Reconstruction of the digital data using NRecon software. Thresholding is done using ImageJ software of type auto local threshold, phansalkar method. From the digitally reconstructed sample, a sub sample of 150³ pixel was analyzed.
3. Result and Discussion

3.1. Reconstruction and Visualization

The reconstructed image of the sample can be visualized to enhance the visibility of the fracture. A 2D fracture formation is shown in the square box marked with the red arrow in Figure 3. Visualization of the 2D slice image as the result from the pressure test at 59 bar is shown in Figure 3 (a). No void natural fracture can be observed in this state of pressure test. This is due to the fact that the natural fractures are filled with minerals from the exposure to the hydrothermal alteration.

The 2D visualization for the pressure test at the 75 bar is shown in Figure 3 (b) where a fracture is visible. The 2D visualization at 91 bar pressure test is shown in Figure 3 (c) which shows a newly formed fracture. During this pressure test the upper side of the previously formed fracture is detached. The detachment of the fractured part of the sample is occurred because the previous it is incapable of resisting the applied pressure, but at the same time, a new fracture was formed.

The 2D visualization at the 107 bar pressure test is shown in Figure 3 (d). It shows the development of the previously formed fracture where fracture intensity and aperture increases. The 2D visualization at the pressure test at 123 bar is shown in Figure 3 (e) where once again, the previously formed fracture was unable to withstand the pressure thus the upper side of the sample was detached. There is no newly formed fracture for the rest of the test (see Figure 3 (f) for the 2D visualization at the 156 bar pressure test).

![Figure 3. Results of 2D reconstruction visualization of fracture formation in rock samples in the thin section to 938: (a) at natural pressure 59 bar; (b) at a pressure of 75 bar; (c) at a pressure of 91 bar; (d) at a pressure of 107 bar; (e) at a pressure of 123 bar; (f) at a pressure of 156 bar.](image)

The fractures which are formed at the pressure of 75, 91 and 107 bars can be observed in 3D visual using CT Vox. Figure 4 (a) shows a fracture formed by uniaxial pressure, which is located at the top edge of the rock. 3D visualization at the 75 bar pressure in Figure 4 (b) indicates a new fracture formed but the one that was formed at 91 bar pressures undergoes a fracture widening causing some parts to
break apart on the upper side of the rock. 3D visualization at the 107 bar pressure in Figure 4 (c) shows a fracture split causing some parts to break apart on the upper side of the rock.

![Figure 4. 3D Visualization Fracture on treatment: (a) Pressure 75 bar; (b) Pressure 91 bar; (c) Pressure 107 bar.](image)

### 3.2. Fracture characteristics

The main characteristics of fracture formation are reviewed based on 3D fracture parameters including total orientation ($\theta$), fracture aperture average ($e$), fracture density ($\Phi$), fracture intensity ($I$) [12] and fractal dimension ($D$) [13].

Total orientation ($\theta$) of the fracture shows the total direction of the fractures. The result from the analysis is shown in Figure 5. The relationship of the fracture orientation as a function of pressure is fitted using polynomial equation which as described in Eq. (1):

$$\theta(P) = 0.0171P^2 - 2.709P + 172.6.$$  

![Figure 5. The relationship of total orientation to pressure](image)
generating a radial axis from the pore/fracture structure, and the size is determined by means of a growing ball with maximum radius determined when the ball touches the pore/fracture wall [14]. Structure separation is one of the functions of CTAn software in analyzing the average aperture fracture \( e \). The result showed average fracture aperture to increase linear at 75-107 bar. The relationship between the average fracture aperture to the pressure can be seen in Figure 6. The relationship of the aperture as a function of pressure test is linear, which can be expressed in Eq. (2) below:

\[
e(P) = 0.0016P - 0.037.
\]  

(2)

![Figure 6. The relationship of average fracture aperture to pressure.](image)

Fracture density is the ratio of total volume of fracture to the total volume of the sample. The relationship between the fracture density to the pressure can be seen in Figure 7. The result showed fracture density to increase exponentially at 75-107 bar. The fracture density as a function of pressure is an exponential equation which can be expressed as Eq. (3):

\[
\Phi(P) = 0.0006e^{0.0402P}.
\]

(3)

![Figure 7. The relationship of fracture density to pressure.](image)

The fracture intensity \( I \) is the ratio between the number of pixels as the result of skeletonization to the sample volume [15]. The fracture intensity indicates the length of the 3D fracture which most likely
to be difficult to be calculated manually due to the existence of some discontinuities. Fracture intensity is calculated using ImageJ software. The relationship of fracture intensity to the pressure can be seen in Figure 8. It is can be observed that the greater the applied pressure, the greater the fracture intensity with a polynomial relationship. The fracture intensity as a function of pressure is an polynomial equation which can be expressed as Eq. (4):

$$I(P) = 5 \times 10^{-6}P^2 - 0.0008P + 0.0342.$$  \hspace{1cm} (4)

**Figure 8.** The relationship of fracture intensity to pressure.

Fractal dimensions of fracture formation due to uniaxial pressure change with pressure treatment 59 bar, 75 bar, 91 bar, 107 bar, 123 bar and 156 bar were calculated using box-counting method. The increase in fractal dimension value is highly influenced by the fracture. The average relation of the fractal dimension to the pore can then be expressed in Eq. (5):

$$D_{por} = 0.0068P + 1.6589.$$  \hspace{1cm} (5)

**Figure 9.** The relationship of average fractal dimension pore to pressure.
The effect of increasing pressure to the safety of this geothermal clay cap was studied by conducting a continuous uniaxial compressive test on the sample. From this test, it is observed that the sample broken at the pressure of 478 bar.

4. Conclusion
The results show that 3D fracture develops as pressure increase are total orientation \( \theta(P) \), aperture \( e(P) \), fracture density \( \Phi(P) \), fracture intensity \( I(P) \) and fractal dimension \( D(P) \). Total orientation and fracture intensity have polynomial to relative to the given pressure. Aperture and fractal dimension are linearly proportional to the give pressure, while the fracture density is exponentially proportional to the give pressure. The effect of increasing pressure to the safety of this geothermal clay cap was studied by conducting a continuous uniaxial compressive test on the sample. From this test, it is observed that the sample broken at the pressure of 478 bar.

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**Acknowledgments**

I would like to thank the Pusat Sumber Daya Mineral, Batubara dan Panas Bumi, Bandung who has provided rock sample to complete this research. This research is partially funded by the research program “PDUPT Kemenristekdikti” grant number 074/UN40.D/PP/2018.