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Introduction to Digital Rock Physics and Predictive Rock Properties of Reservoir Sandstone

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Abstract. Rock properties analysis (porosity, permeability, elastic modulus, and wave velocity) of the rock is important to note as one of the methods to determine the characteristics of the reservoir rock. Rock properties can calculated in conventional (laboratory), indirect (inversion of seismic waves), and digital computation (Digital Rock Physics). This paper will introduce and discuss the digital calculation/simulation and empirical equation to predict the value of the rock properties from reservoir sandstone. The data used is the samples of the data sandstone core (reservoir) subsurface in an oil field. The research method is to combine the data from a thin layer, a digital image of rocks in three-dimensional (µ-CT-Scan), and empirical approaches of the equations of permeability on rocks and Lattice Boltzmann equation. Digital image of a scanned using µ-CT-Scan used to determine value rock properties and pore structure at the microscale and visualize the shape of the pores of rock samples in 3D. The method combined with rock physics can be powerful tools for determining rock properties from small rock fragments.

1. Introduction

Reservoir rocks possess a certain characteristic which can be identified by several physical parameters. Among many of the physical parameters are the porosity and permeability. The characterization is a process of elaborating its characteristic qualitatively and quantitatively by using the available data. Characteristics provided as information regarding physical parameters from reservoir rock is essential to understand the reservoir better.

The characterization of reservoir rock can be conducted directly in-situ, or also in the laboratory. In this paper, we utilized analysis of digital images (Digital Rock Physics; DRP) to obtain information regarding the characteristic of the reservoir rock [1, 2, 3, 4]. This method utilizes the absorption of X-ray to obtain the digital image from the rock. The goal of this research is to estimate porosity, permeability and elastic properties of the reservoir sandstone using computer-based simulation and empirical method. Digital rock physics (DRP) aims at providing qualitative and quantitative understanding of flow transport units as well as geometrical properties of rocks. Some of the rock properties are extremely difficult, if not impossible, to measure in the laboratory. Thus, DRP in conjunction with laboratory measurements, will compliment and complete well log analysis with not

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only detailed information but also with new kinds of insights. Such well logs enhance analysis of reservoirs and will open a way for economic exploration and better recovery of hydrocarbon [5].

2. Data and Basic Theory

The sample data used in this research is a core of reservoir sandstone. Name sample is Ngrayong-54 which diameter 5 cm, length 15 cm, porosity 0.24 and density 2.3 gram/cm^3. Subsequent after acquiring the digital images, porosity is calculate as follows:

$$\phi = \frac{V_{pore}}{V_{total}} = 1 - \frac{V_{matriks}}{V_{total}} \tag{1}$$

V_{pore} is volume of pore and V_{total} is the volume rock. The simple bounds for an isotropic linear elastic composite, defined as giving the narrowest possible range without specifying anything about the geometries of the constituents, are the simple effective medium theory is the Voigt bound (illustrated by Figure 1). The Voigt bound calculated effective elastic modulus M_V, from the volume fraction N phase f_i, and elastic modulus N phase fraction M_i as follows:

$$M_V = \sum_{N=1}^{N} f_i M_i \tag{2}$$

Figure 1. Effective medium theory simple illustration using Voigt upper bound.

The empirical calculation to determine elastic properties is the P-wave velocity, S-wave velocity, Bulk Modulus and Shear Modulus. P-wave velocity (V_p) and S-wave velocity (V_s) is calculated as follows [6]:

$$V_p = (1-\phi)^2 V_m + \phi V_f$$
$$V_s = (1-\phi)^2 V_m \sqrt{\frac{(1-\phi)\rho_m}{(1-\phi)\rho_m + \phi\rho_f}} \tag{3}$$

V_m is the Velocity in the mineral, V_f is the velocity in the fluid, ρ_m is the density of mineral and ρ_f is the density fluid. Bulk modulus (K) and Shear Modulus (G) is calculate as follows:

$$K = \rho V_p^2 - \tfrac{4}{3}G$$
$$G = \rho V_s^2 \tag{4}$$

One of the characteristics of the reservoir rock is the acoustic impedance (AI). Acoustic impedance is calculated using equation [6]:

$$AI = \rho V_P \tag{5}$$

Then, the rock ability to pass through the pore fluid is expressed by the permeability. Absolute permeability appears in Darcy's law as a constant coefficient relating fluid, flow, and the porous medium parameters as follows:

$$\frac{Q}{A} = -\frac{k}{\mu}\frac{\Delta P}{L} \tag{6}$$

To calculate permeability, we simulate fluid flow using Lattice Boltzmann method that is as follows [7]:

$$k = \frac{Q\mu}{A}\frac{1}{dP/dL} = \frac{\mu\langle v\rangle}{dP/dL} \tag{7}$$

Where Q is the fluids debit, A is the surface area, μ is the viscosity, and dP/dL is the differential of pressure by the length.

3. Rock Imaging

The process of DRP begins with an image of a large rock sample acquired at a relatively coarse resolution to cover a large field of main cube. At this stage, rock fabrics larger than the image resolution are resolved while smaller ones are unresolved (sub-cube). Information concerning the unresolved rock fabrics is analysis from additional images acquired at a finer resolution and smaller field of view. The information from resolved and unresolved rock fabrics are average from the small-scale image and back into the large-scale image. In general, the stage of the DRP analysis shown in Figure 2. Multi-scale DRP provides a promising method to characterize rocks. They can be roughly summarized as follow:

Digital rock imaging using µCT-Scan: the sample is later converted into digital images µCT-Scan device SkyScan 1173 which is installed in the BSC-A building, Institut Teknologi Bandung
Image segmentation: digital image result is separated between the pore and solid matrix rock. This process is called thresholding.
Rock imaging at the finer resolution and smaller field of view: Thresholding result made in the form of 2D and 3D (cube). Furthermore, the main cube made into the small cube (sub-cube) to determine variation the physical properties of the rock.
DRP analysis, 2D and 3D analysis: the next step is to calculate the percentage of pore section and solid rock matrix to determine the value of porosity every sub-cube. Permeability values were calculated using Lattice Boltzmann equation. The volume fraction of each constituent mineral rock calculated to determine effective medium theory. Then, calculation elastic properties of sandstone using empirical equation.

Figure 2. DRP data processing stages on sandstone sample. The stage begins with digital image processing to the calculation porosity, permeability, and elastic properties using empirical equations.

A variety of imaging and detection techniques have been used to gain insights into rocks. Ideally, the image resolution being used should resolve all significant rock features and provide a large field of view. Due to limitations in imaging technology both image resolution and image scale are overly compromised. Figure 3 imaging of sandstone sample. Figure 3a is the original image slice (2D), has a dimension 300×300 pixels. They have a gray-scale color image. Black is the pore and gray is the solid matrix of rock. Black image shows pore (air), the gray color shows solid matrix low density, and bright white color shows solid matrix higher density. Figure 3b is the image made in the thresholding process from Figure 3a. Black is the pore fraction and white are the solid matrix of the rock. Figure 3c and 3d is the sub-cube from the original image. The Figure 3e and Figure 3f are the 3D image from the sub-cube.

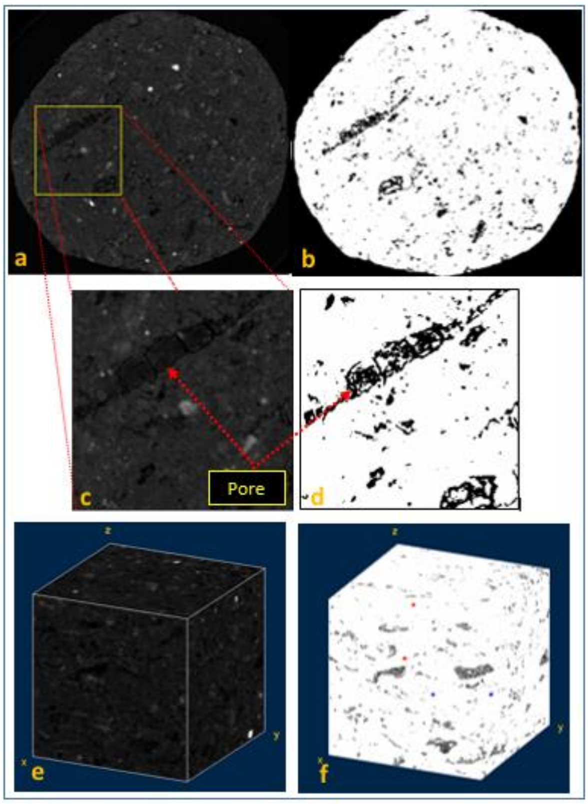

Figure 3. Digital rock physics was processed of sandstone. (a) 2D original image (gray scale), (b) image made in thresholding, (c) sub-cube from the original image, (d) threshold image from c, (e) 3D image from c by dimension 300×300×300 pixels, and (f) 3D threshold image from e.

4. Result and Discussion

Calculation of porosity values of obtained from Figure 3d. Porosity values obtained from 16 sub-cube to determine variations. Then, permeability values obtained from Lattice Boltzmann equation from 16 sub-cube. Elastic properties values obtained using equation (3), (4), and (5). The volume fraction of the constituent mineral rock consisting of biotite (4%) and feldspar-quartz-clay (96%) from the solid matrix of rock. The calculation results are shown in Table 1. The Chart on the calculation of permeability, elastic modulus, seismic wave velocities, and acoustic impedance as a function of porosity is shown in Figure 4. In Figure 4a, the permeability values are increasing with increasing porosity values. Permeability value varies between 160-6000 mD with the average permeability is

2700 mD. This value indicates that the sandstone sample can accommodate and passes fluid well. Thus, this sandstone sample can be a good reservoir rock.

Table 1. Summary of the results calculation values of the porosity, permeability, and elastic properties of the sample sandstone.

Sub Cube	Porosity	Permeability (mD)	V_p (km/s)	V_s (km/s)	Shear Modully (GPa)	Bulk Modully (GPa)	Acoustic Impedance (Kg/m^3 Km/s)
1	0.241	1989	3.21	2.00	10.89	13.56	8353.17
2	0.211	824	3.47	2.16	12.72	15.82	9026.42
3	0.332	6420	2.49	1.55	6.52	8.15	6470.62
4	0.159	160	3.94	2.46	16.42	20.41	10255.21
5	0.287	3909	2.84	1.76	8.47	10.56	7371.54
6	0.263	2880	3.03	1.89	9.67	12.06	7876.04
7	0.302	5022	2.72	1.69	7.78	9.71	7064.71
8	0.284	3760	2.86	1.78	8.62	10.74	7433.69
9	0.215	835	3.44	2.14	12.45	15.50	8932.61
10	0.326	5820	2.53	1.58	6.76	8.44	6587.35
11	0.274	3195	2.94	1.83	9.10	11.34	7638.98
12	0.208	486	3.50	2.18	12.90	16.05	9090.23
13	0.295	4350	2.77	1.73	8.10	10.11	7209.20
14	0.188	380	3.68	2.29	14.27	17.74	9560.25
15	0.253	2459	3.11	1.94	10.21	12.72	8091.17
16	0.226	867	3.34	2.08	11.75	14.63	8677.94

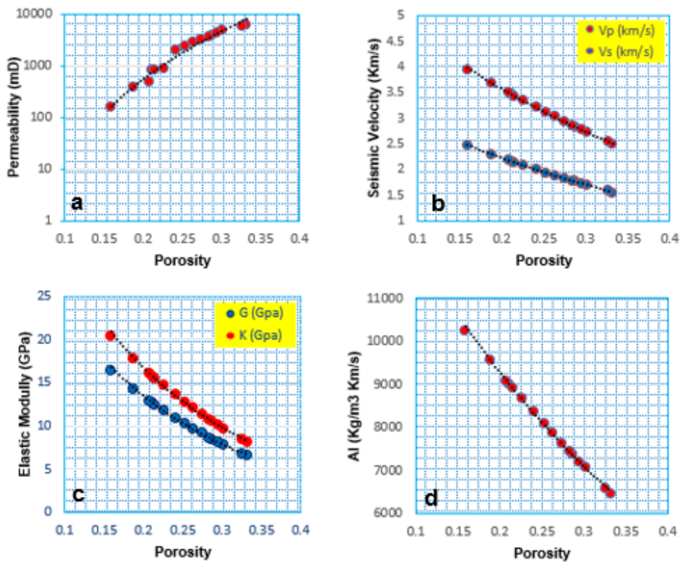

Figure 4. The calculation of permeability and elastic properties of sandstone sample. (a) estimation of permeability, (b) estimation of V_p and V_s, (c) estimation of Bulk modulus and shear modulus, and (d) estimation of acoustic impedance.

Figure 4b shows the variation of the seismic wave velocities decreases with increasing porosity value exponentially. The red marker is the *P*-wave velocity and blue is the *S*-wave velocity. *P*-wave velocity value varies between 2.49 km/s – 3.94 km/s with the average value is 3.12 km/s. *S*-wave velocity value varies between 1.55 km/s – 2.46 km/s with the average value is 1.94 km/s. Figure 4c shows the variation of the elastic modulus decreases with increasing porosity value exponentially. The red marker is the bulk modulus and blue is the shear modulus. Bulk modulus value varies between 8.15 Gpa – 20.41 Gpa with the average value is 12.97 Gpa. Shear modulus value varies between 6.52

Gpa – 16.42 Gpa with the average value is 10.41 Gpa. Figure 4d shows the variation of the acoustic impedance decreases with increasing porosity value exponentially. Acoustic impedance value varies between 6450 (Kg/m^3 Km/s) – 10250 (Kg/m^3 Km/s) with the average value is 8100 (Kg/m^3 Km/s).

5. Conclusion

The conclusions of this paper are: (1) μ-CT image is able to visualize the micro structure of rocks such as the pore and density matrix, (2) μ-CT image combined with digital computation can deliver the result of pore visualization, porosity value prediction, permeability value prediction, fraction of high-low density rock matrix, and elasticity of sandstone samples, (3) The rock properties such as porosity, permeability, and elastic properties have done calculated using digital imagining analysis and empirical equation, and (4) The method combined with rock physics can be powerful tools for determining rock properties from small rock fragments.

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