



Effectiveness of Digital Rock Methods over other Physics Based and Empirical Techniques for Permeability Estimation: A Multiscale Approach

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Keywords

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Abstract

Understanding fluid behavior within subsurface formations necessitates a comprehensive examination of the pore space and the associated pore-scale processes. Digital rock physics (DRP), a rapidly developing discipline at the interface of geosciences and computer sciences, offers a promising approach to unravel the complexities of pore-scale physics and the resulting fluid flow in the sub-surface. In contrast to traditional laboratory studies, which are often time-consuming, expensive, and limited in capturing the true intricacies of pore networks, DRP can be employed to analyze and predict effective porosity and permeability, two critical sub-surface parameters that governs fluid flow. The present study provides a scale dependent comparative analysis of estimating permeability using numerical and empirical methods such as, the Lattice Boltzmann simulation method (LBM), the Kozeny-Carman empirical relation, and laboratory measurements. The findings of the study reveal that the permeability values derived from the Kozeny-Carman equation are higher compared to those obtained from LBM simulations. This disparity can be attributed to the simplifications and assumptions inherent in the Kozeny-Carman model, given its macroscopic nature. The equation assumes a simplified representation of pore geometry and assumes uniform flow through interconnected channels, neglecting the intricate flow behavior at the pore scale. The scale-dependent comparative analysis highlights the disparities in permeability estimation between the Kozeny-Carman equation and LBM simulations. The present study is a preliminary investigation carried out on rock samples that exhibit similarities to Lithuanian reservoirs. Its primary aim is to establish a foundational basis for future research concerning the storage of CO₂ and hydrogen within Lithuanian reservoirs.

Introduction

Reservoir characterization is a crucial process that involves accurate quantification of the petrophysical properties necessary for the exploration and production of hydrocarbon reservoirs. While porosity can be directly measured in the field, determining permeability directly in the field using well logging or any other geophysical prospecting method is extremely difficult and to say the least is not quantifiable. Therefore, laboratory studies are conducted on the core samples to determine their petrophysical properties. These experiments are designed to consider factors such as grain size, packing, heterogeneity and the scale of investigation. However, these laboratory studies can be time consuming, expensive and destructive in nature (Dvorkin et al., 2003; Kalam, 2012; Sharma et al., 2021). In recent years, Digital Rock Physics (DRP) has emerged as a computational approach that enables the estimation of petrophysical parameters without the need for physical core analysis. DRP utilizes advanced imaging techniques and computational models to simulate fluid flow through a digital representation of the rock sample, providing valuable insights into rock behavior (Andrae et al., 2013). It can generate a large database that captures the intricate details of the rock microstructure and fluid behaviour (Ceron et al., 2013).

In this study, the petrophysical parameters are estimated using scanned images obtained from Micro Xray Computed Tomography (MXCT) and Field Emission Scanning Electron Microscopy (FESEM) scanning techniques. This is a feasibility study conducted on rock samples obtained from formations analogous to Lithuanian reservoirs. These rock samples belong to sandstone formation, primarily composed of quartz as the dominant mineralogy with



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minor occurrences of clay minerals. The selection of these rock samples is based on their similarity in mineralogy, porosity and permeability to Lithuanian formations. The objective of this study is to lay the foundation for further investigations into the storage of CO₂ and hydrogen in Lithuanian reservoirs. (Malik et al., 2023a, 2023b; Pal et al., 2023).

Theory

Fluid storage and flow in the subsurface formations are governed by the processes that occur at the pore scale. Therefore, it is imperative to closely examine the phenomenon taking place at this microscopic level and study the impact of fluid on both the pore space and solid matrix. The two important subsurface parameters that play a major role in fluid flow are porosity and permeability.

Porosity estimation:

One of the key sub-surface parameters that affects the fluid flow is porosity. It is defined as the measure of empty space within a medium. In the present work, porosity is estimated using an unsupervised machine learning algorithm, known as K-means algorithm.

K-means algorithm

K-means is a clustering algorithm employed for segregating the dataset into different clusters or groups. The algorithm operates iteratively and seeks to minimize the intra-cluster variance (defined by equation 1), which is the sum of squared distances between data points and their assigned cluster centroid, (defined in equation 2).

The intra-cluster variance is defined as follows, (Cortina-Januchs et al., 2011)

$$Z = \sum_{i=1}^n \sum_{j=1}^k \|x^{(i)} - c_j\|^2, \quad (1)$$

Where, $\|x^{(i)} - c_j\|^2$ is the Euclidean distance between the data point $x^{(i)}$.

$$c_j = \frac{1}{n} \sum_{i=1}^n x_j^{(i)} \quad (2)$$

Where, n is the number of data points in the jth cluster and $x_j^{(i)}$ is the ith data point.

Permeability estimation:

The second key parameter that plays a significant role in the pore scale investigations is permeability. It is an intrinsic characteristic of a porous medium and

is a measure of its ability to transmit fluids. In the field of DRP, permeability is widely regarded as a reliable property that can be measured using DRP technique (Knackstedt et al., 2009; Dvorkin, 2011). There are different methods to determine the permeability of a core sample. This paper provides a comparison of the permeability values obtained from Kozeny-Carman empirical relation, LBM simulation method and laboratory measurements.

Kozeny-Carman Equation

The Kozeny-Carman equation is an empirical relation used to estimate the permeability of porous media based on their porosity and specific surface area. The equation is derived from the assumption that fluid flow occurs through a network of interconnected spherical grains. According to the Kozeny-Carman equation, the permeability (k) of the porous medium is given by:

$$k = C * \frac{\Phi^3}{(1 - \Phi)^2} * \frac{1}{Sv_{gr}^2} \quad (3)$$

Where, Φ = porosity of the medium, Sv_{gr} = Specific surface area of grains and C = Dimensionless constant.

The specific surface area for spherical grains can be defined by the equation (Tiab and Donaldson, 1996, 2015):

$$Sv_{gr} = \frac{6}{d} \quad (4)$$

Where, d = grain diameter

Lattice Boltzmann Method (LBM)

The Lattice Boltzmann method is a computational fluid dynamics technique that simulates fluid flow at the mesoscopic level (Chen and Doolen, 1998). It is based on Boltzmann equation (defined by equation 5), which assumes that a fluid consists of numerous particles. In LBM these particles are represented by a probability distribution function (PDF), denoted as $f(x,v,t)$ at discrete lattice nodes. The PDF describes the likelihood of finding a particle at a particular position (x) with a specific velocity (v) at a given time (t). The PDF is updated at each time step to simulate the behaviour of the fluid.

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \Delta f = \Omega \quad (5)$$

Here,

$f(x,t)$ = particle distribution function, and Ω = collision operator.

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LBM offers advantages such as flexibility in handling complex geometries, and the ability to simulate multiphase and multicomponent flows (Mohamad, 2011).

Methodology

In this study, digital volumes of sandstone rocks are used to determine the petrophysical parameters, which are benchmarked with the laboratory measurements.

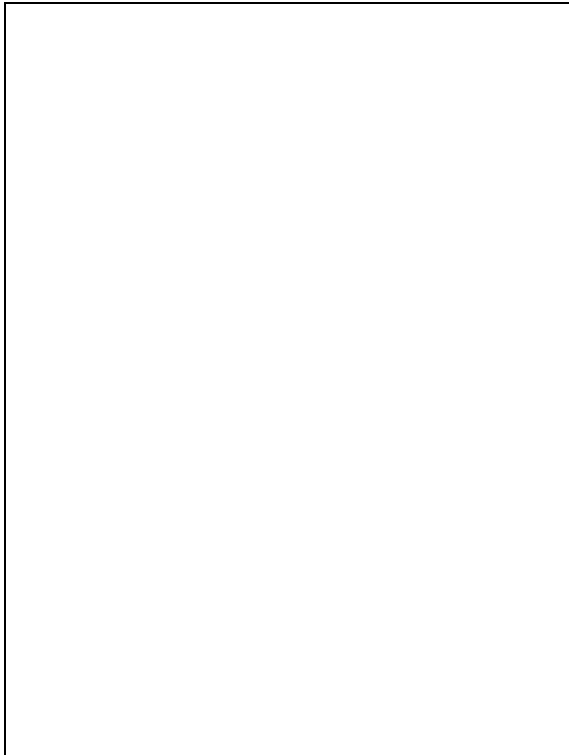


Figure 1: Flowchart of the methodology adopted.

The permeability estimation from Kozeny-Carman equation requires the estimation of grain diameter. A spherical distribution of grains is assumed.

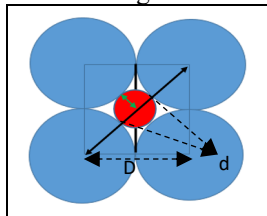


Figure 2: Calculation of grain diameter from pore throat.

In the above figure, the length of the side of the square = grain diameter = D

$$\text{Length of the diagonal of square} = \sqrt{2} * D$$

Diameter of the pore throat (shown by red circle in figure 2) = d

Diameter of the pore throat =

(diagonal of the square – 2 * radius of the grain)

$$\Rightarrow d = \sqrt{2} * D - D$$

$$\Rightarrow d = D (\sqrt{2} - 1)$$

$$\text{Grain diameter (D)} = d / (\sqrt{2} - 1) \quad (6)$$

Results and Discussion

In the present study, three (03) sandstone samples with dominant quartz mineralogy and clay, were used. The core samples with diameter = 1.5” and length = 2” are scanned at a resolution of 22µm using MXCT imaging technique. Also, a small cube of approximately 1cm³ is used for imaging using FESEM technique.

MXCT imaging

The segmentation is performed using k-means machine learning algorithm to determine the porosity of the core samples. Prior to porosity estimation the quality of the images is improved using contrast limited adaptive histogram equalization (CLAHE) method.

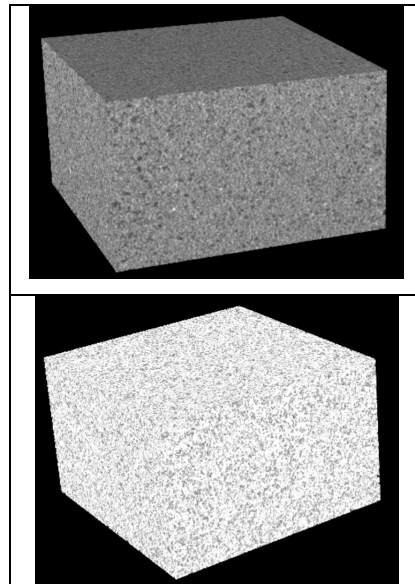


Figure 3: The scanned 3D volume (top) of the core sample obtained from MXCT imaging and its segmented 3D volume (bottom). The 3D volume size is 940 X 940 X 601.

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The porosity values obtained from k-means algorithm is benchmarked with the laboratory measured values, shown in Table 1.

Table 1: Benchmarking of the porosity values obtained from K-means algorithm with the laboratory measure values.

Sample	Porosity using K-means (%)	Laboratory measured porosity (%)	Error (%)
S1	19.98	21.6	7.5
S2	19.70	19.9	1.0
S3	19.99	20.22	1.1

The error percentage in Table 1 is maximum for the S1 sample, whereas for S2 and S3 the error is within the acceptable limits. The difference in the DRP derived porosity value can be attributed to the presence of clay minerals in S1 sample. Clay minerals exhibit variations in density and composition, which can affect their appearance in MXCT images. For example, if clay minerals are mixed with other materials or if there are variations in their water content, it can result in different levels of X-ray absorption and, consequently, different shades of gray in the MXCT images. Therefore, the presence of clay minerals in the MXCT images can be observed as either grains or pore space, making it challenging to accurately segment the pore space from grains. Thus, contributing to the high error percentage in S1 sample.

LBM simulation

The LBM simulation is performed on the segmented 3D volume of the core sample. To perform LBM simulation, an open-source code Palabos (parallel lattice Boltzmann solver) is used (Latt et al., 2021). It uses Darcy's law to determine the permeability of the samples.

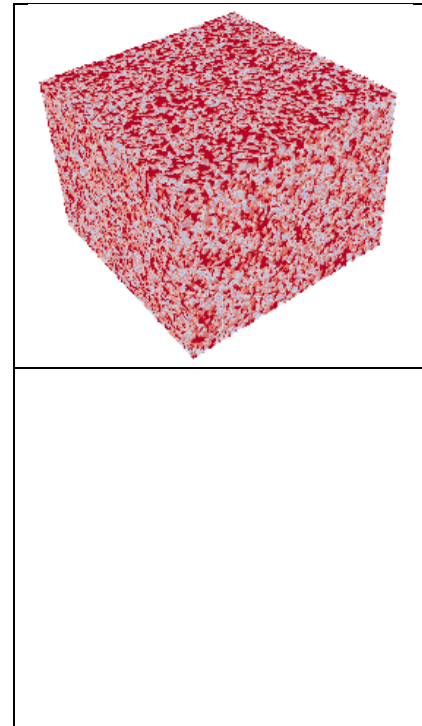
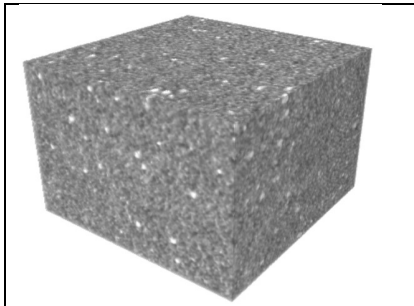
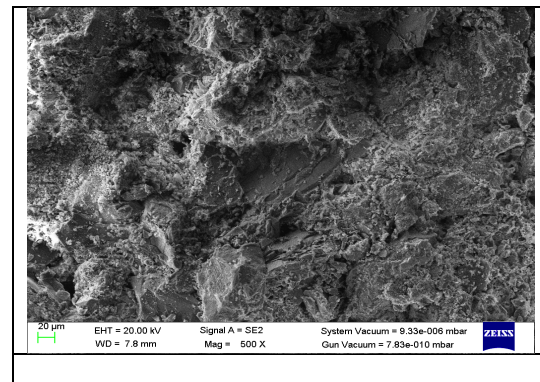


Figure 4: Scanned 3D volume (top), its segmented 3D volume (middle) and LBM simulated output (bottom), where blue thread like distribution shows the fluid flow through the pore space.

FESEM imaging

The images obtained from FESEM are used to determine the dominant pore throat size. This is then used to calculate the grain diameter using equation 6. Additionally, the scale defined at the bottom of the FESEM images is used to define the resolution of the images, which is important for accurate measurements.



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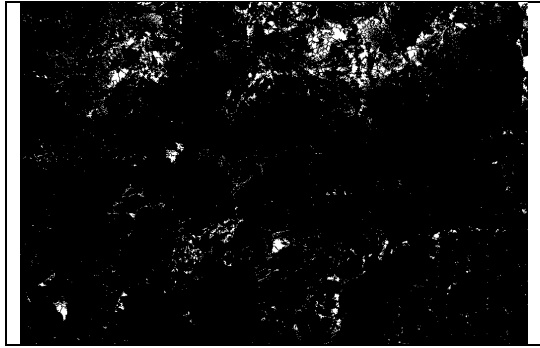


Figure 5: FESEM scanned image of the rock sample (top) and its segmented image (bottom).

The segmented image is used to show the distribution of pore throat sizes in the rock sample. The dominant pore throat size is determined from the pore throat size distribution plot shown in figure 6, which is then used to calculate the grain diameter.

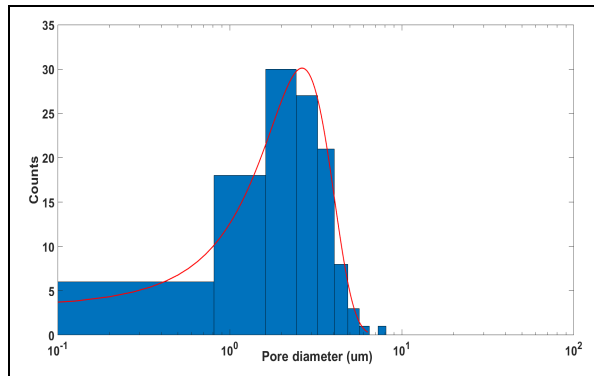


Figure 6: Pore size distribution.

Comparison of the permeability values

The permeability values obtained from LBM simulations and Kozeny-Carman equation, are benchmarked with the laboratory measured values.

In the Kozeny-Carman equation, permeability estimation relies on the assumption that the porous medium is isotropic, homogeneous and possesses a uniform pore size. However, this assumption does not accurately reflect the complexity of real porous media. In contrast, LBM simulations consider the detailed interactions between the fluid particles and porous medium, providing a more accurate representation of the flow behavior.

Table 2: A comparison of the permeability values obtained from LBM, Kozeny-Carman relation and laboratory measurements.

Sample	Permeability value (mD)		
	LBM	Kozeny-Carman equation	Laboratory measurement
S1	316	237	275
S2	91	126	62
S3	390	500	327

Consequently, the difference in permeability values obtained from the Kozeny-Carman equation and LBM simulations (as shown in Table 2) can be attributed to the assumptions and limitations of the Kozeny-Carman equation, which may result in overestimation of the permeability values. In the present study, the difference in values does not have a significant impact since we are considering the order of magnitude, which aligns accordingly.

Conclusions and Future Work

We have presented a comparison of the permeability value estimation from different methods, which includes LBM simulation, Kozeny-Carman empirical relation and laboratory measurements using images obtained from MXCT and FESEM scanning techniques. We find that:-

- The k-means algorithm adopted for segmentation gives results in agreement with the laboratory measurements.
- The difference in porosity values can be attributed to the presence of clay in samples.
- The permeability values obtained from LBM, Kozeny-Carman equation and laboratory method gives results in agreement with each other, since we are considering the order of magnitude which aligns accordingly.

The present work will be extended:

- To create feasibility models that explore the interactions between rocks and various scenarios involving temperature, pressure, and fluid phase behaviors.
- To assess the feasibility and potential of utilizing Lithuanian reservoirs for CO₂ and hydrogen storage purposes.
- To investigate geochemical reactions and the geo-mechanical behavior of rocks resulting from injection of CO₂ and hydrogen, to assess



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the long-term storage potential of these gases within the Lithuanian formations.

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