Estimation of porosity and permeability spatial distribution based on X-ray CT images

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OUTLINE

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INTRODUCTION

Motivation and Purpose
• Quantifying the hydraulic conductivity and permeability of porous media is an important step in understanding a variety of physical systems in which fluids move through soils and regolith.

• The hydrogeological parameters of deep cores is key to explore energy or store CO$_2$. 

MOTIVATION
MOTIVATION

• X-ray Computed Tomography (CT) is a nondestructive technique for visualizing interior features within solid objects.

• The core is difficult to collect, so we don’t want to destroy it.
MOTIVATION

• It’s a challenge to drill the core when it is unconsolidated.

• It’s hard to get the lateral permeability.

• A pure (Computational Fluid Dynamics) CFD to simulate $K$ is time consuming and cannot work with other well-established numerical package for porous media.
PURPOSE

• Get the pore structure and estimate the porosity and permeability of the sample by the X-ray CT images.
LITERATURE REVIEWS
X-ray computed tomography (X-ray CT) is a nondestructive internal core structure characterization technique. (Fuyong Wang, 2016)

- Homogeneous High density
- Lineal or stripy deep region
- Dark blocks

(a) Matrix sample  (b) Fractured sample  (c) Vuggy sample
A well-known relationship between permeability and the properties of pores was proposed by Kozeny and later modified by Carman. The resulting equation is largely known as the Kozeny–Carman (KC) equation. (Chapuis R.P. & M. Aubertin, 2003)
**RELATIONSHIP OF POROSITY AND PERMEABILITY**

- Peng Xu and Boming Yu summarize some modifications of the KC equation. (2007)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Permeability equation</th>
<th>Media</th>
</tr>
</thead>
<tbody>
<tr>
<td>McGregor [8]</td>
<td>$K = \frac{a^2}{16c(1-\phi)} \phi^3$</td>
<td>Textile assembly</td>
</tr>
<tr>
<td>Bourbié et al. [9]</td>
<td>$C \phi^{n+2} \frac{d^2}{72\tau^2(1-\phi)^2} \left(\frac{(C_{1}+C_{2}+1)^2}{(1+C_{2})^2}\right)$</td>
<td>Porous media</td>
</tr>
<tr>
<td>Panda and Lake [10]</td>
<td>$K = \frac{\phi^3}{c(1-\phi)^n}$</td>
<td>Unconsolidated</td>
</tr>
<tr>
<td>Shih et al. [11]</td>
<td>$K = \frac{\phi^{n+1}}{c(1-\phi)^n}$</td>
<td>Glass and fiber</td>
</tr>
<tr>
<td>Rodriguez et al. [12]</td>
<td>$K = \frac{\phi^3}{c(1-\phi)^n}$</td>
<td>Square particles</td>
</tr>
<tr>
<td>Koponen et al. [13]</td>
<td>$K = \frac{\phi^{n+1}}{c(1-\phi)^n}$</td>
<td>Sanstone carbonate</td>
</tr>
<tr>
<td>Mavko and Nur [14]</td>
<td>$K(md) = C \phi^{3}/(1-\phi)^3/\phi_{c} + \phi_{c}$</td>
<td>Fine particle filter cakes</td>
</tr>
<tr>
<td>Bayles et al. [15]</td>
<td>$K = C \phi^{2+3n}/(1-\phi)^2$, here $C = c/(8s_{c}^2)$</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Pape et al. [16]</td>
<td>$K = \frac{\phi^{2+n}}{8s_{c}^2(3r_{c}^2(1-\phi))}$</td>
<td>Porous media</td>
</tr>
<tr>
<td>Civan [17]</td>
<td>$K = \sqrt{\frac{K}{\phi}} \frac{n}{(\phi)}$</td>
<td>Fiber mats vesicular rocks</td>
</tr>
<tr>
<td>Costa [18]</td>
<td>$K = C \phi^{n-1}$</td>
<td></td>
</tr>
</tbody>
</table>

$c$ – permeability factor, $n$ – empirical exponent, $\gamma$ – skewness of PSD, $C_{1}$ – coefficient of variation of PSD, $\phi_{eff}$ – effective porosity, $\phi_{c}$ – percolation threshold, $r$ – grain radius, $D$ – fractal dimension, $\Gamma$ – interconnectivity parameter.
KOZENY-CARMAN EQUATION

\[ K = C \frac{g}{\mu_w \rho_w} S^2 D_R^2 (1+e) \]

- **K**: Hydraulic Conductivity
- **C**: shape and tortuosity of channels
- **S**: specific surface (m²/kg)
- **g**: gravitational constant
- **e**: Void Ratio = n/(1-n)
- **\( \mu_w \)**: Dynamic viscosity of water
- **\( \rho_w \)**: Density of water
- **\( \rho_s \)**: Density of solids
- **\( D_R \)**: specific weight of solids

\[ k = \frac{\rho g}{\mu} \]

- **k**: Intrinsic Permeability (m²)
- **C**: shape and tortuosity of channels
- **S**: specific surface (m²/kg)
- **g**: gravitational constant
- **n**: Porosity
- **\( \rho_w \)**: Density of water (kg/m³)
- **\( \rho_s \)**: Density of solids (kg/m³)
- **\( D_R \)**: specific weight of solids
The Kozeny-Carman equation is given by:

\[ k = C \frac{n^3}{\rho_w S^2 D_R^2 (1-n)^2} \]

\( k \): Intrinsic Permeability \( (m^2) \)

\( C \): shape and tortuosity of channels

\( S \): specific surface \( (m^2/kg) \)

\( g \): gravitational constant

\( n \): Porosity

\( \rho_w \): Density of water \( (kg/m^3) \)

\( \rho_s \): Density of solids \( (kg/m^3) \)

\( D_R \): specific weight of solids

Carman (1939) suggests that a factor \( C = 0.2 \) gives the best fit with experimental results.
METHODOLOGY

Process and Sample
X-ray Computed Tomography (CT) is a nondestructive technique for visualizing interior features within solid objects. A CT slice image is composed of voxels (volume elements).
• Sample: 彰濱觀測井 (TPCS-M1) R425-1
• Location: 2409m depth, Kueichulin Formation Yutengping Sandstone (KCY)
• Fine-grained sandstone
• Size = 4904 x 4904 voxels
• 1 voxel = 2 μm
PRELIMINARY RESULTS
3092 voxels

4904 voxels

2000 voxels

1500 voxels

4904 voxels

50 voxels

50 voxels

50 voxels
The color means the surface area of the pore in each mesh.
\[ k = C \frac{n^3}{\rho_w S^2 D_R^2 (1-n)^2} \]

<table>
<thead>
<tr>
<th>R425_1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length (m)</strong></td>
<td>2.0E-4</td>
</tr>
<tr>
<td><strong>Total Volume (m³)</strong></td>
<td>8.0E-12</td>
</tr>
<tr>
<td><strong>Solid Volume (m³)</strong></td>
<td>6.8E-12</td>
</tr>
<tr>
<td><strong>Solid Mass (kg)</strong></td>
<td>1.41E-08</td>
</tr>
<tr>
<td><strong>Porosity</strong></td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Density (sample) (kg/m³)</strong></td>
<td>2070</td>
</tr>
<tr>
<td><strong>Density (water) (kg/m³)</strong></td>
<td>1000</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Surface Area (m²)</strong></td>
<td>1.97E-07</td>
</tr>
<tr>
<td><strong>Specific Surface Area (m²/kg)</strong></td>
<td>14</td>
</tr>
</tbody>
</table>

Refer to R371-1A, which is in the same location (楊盛博, 2015)

Carman (1939)
Average porosity: 0.182
Average permeability:
$1.1 \times 10^{-12}$ m$^2$
The experimental results from Prof. Dong’s lab:

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample</th>
<th>Porosity (%)</th>
<th>Permeability ($m^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kueichulin Formation</td>
<td>R425-1</td>
<td>30.3 ~ 23.7</td>
<td>$7.3 \times 10^{-13} ~ 4.2 \times 10^{-13}$</td>
</tr>
<tr>
<td>Yutengping Sandstone, KCY</td>
<td>R425-1</td>
<td>30.3 ~ 23.7</td>
<td>$7.3 \times 10^{-13} ~ 4.2 \times 10^{-13}$</td>
</tr>
<tr>
<td></td>
<td>R371-1A</td>
<td>18.6 ~ 15.4</td>
<td>$1.0 \times 10^{-13} ~ 2.5 \times 10^{-14}$</td>
</tr>
</tbody>
</table>

Data/ Figures source: Prof. Dong’s lab

![Porosity and Permeability plots](image)
Find the value when there is no confining pressure.

\[ K_{OC} = 1.73 \times 10^{-11} \cdot \left(\frac{P_{pl}}{P_0}\right)^{-0.5245} \cdot \left(\frac{P_e}{P_{pl}}\right)^{-0.1118} \]

Average permeability from CT images: \(1.125 \times 10^{-12} \text{ m}^2\)

Permeability from test: \(1.13 \times 10^{-12} \text{ m}^2\)
CONCLUSION
1. Finish the process of the porosity and permeability estimation through the Avizo software.

2. In sample R425_1, if we apply the appropriate setting in Avizo software, we can get the similar results compared with the high confining pressure test.
FUTURE WORKS
1. Estimate the lateral k value by changing the variable C in the KC equation.

2. Apply the process to estimate the other samples.

3. Find the real distribution of pores based on the thin section images (SEM).
THANKS FOR LISTENING.😊