

Poromechanics Investigation at Pore-scale Using Digital Rock Physics Laboratory

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Abstract: Understanding the rock structure at nano to micro scale is of growing importance in geology, oil and gas, and hydrology. New approaches that relies on a variety of high resolution 3D imaging techniques offered tremendous potential. These new approaches, in the meanwhile, introduce significant new challenges. Starting from digital imaging data, this paper introduces an image-to-simulation framework. With highly efficient, interactive, and user friendly software algorithms powered by Avizo and Comsol Multiphysics, porous rock structure can be accurately extracted and numerical simulations can be conducted, based on which existing rock models can be validated and compensated with much more physical insights.

Keywords: Rock Physics, 3D Imaging, from image to simulation.

1. Introduction

Understanding the rock structure at nano to micro scale is of growing importance in geology, oil and gas[8], and hydrology. New approaches that relies on a variety of high resolution imaging techniques, including but not limited to thin section analysis, FIB-SEM, and 3D X-ray micro CT imaging, revealed unprecedented details of the porous rock structure.

Digital rock microstructure extracted from these high resolution images can be used to simulate coupled physics, which offer tremendous potential towards an improved understanding of physics at the pore-scale and beyond. These new approaches, in the meanwhile, introduce significant new challenges. On one hand, the large amount of data needs to be processed and useful information has to be extracted. On the other hand, such simulations must be benchmarked with either previously known exact theoretical solutions or physical lab measurements. Nevertheless, such digital rock simulations can help improve or validate

theoretical rock physics models (Hudson model [4]), which almost always oversimplify either the rock pore geometry or complexity of coupled physics phenomenon. Moreover, the physical insight gained from these simulations can potentially explain the mismatch between laboratory measurements and models[5].

Starting from digital imaging data, this paper introduces an image-to-simulation framework which addresses both aforementioned challenges. With highly efficient, interactive, and user friendly software algorithms powered by Avizo and Comsol Multiphysics, porous rock structure can be accurately extracted and benchmarked numerical simulations can be conducted, based on which existing rock physics models can be validated.

2. Theoretical background

Rocks are heterogeneous porous media, varying in geometry, mineralogy, texture, etc. Rock void or pore space is often filled with a variety of gas, fluid, solid, or more commonly a mixture.

Gassmann's equation [2] is widely used in exploration geophysics to predict the effective elastic properties of rocks with fluid-filled interconnected pores. It is also known as a fluid substitution equation because it predicts the change in effective elastic response by replacing one chemically inert fluid with another in an arbitrary rock pore-space. This classical equation is inapplicable for rocks filled with viscous solid-like materials, such as heavy oil and bitumen.

Recently, Ciz and Shapiro [1] generalized Gassmann's equation for a solid pore-filling material. However, their generalized equation requires specifying a heuristic rock compressibility parameter which cannot be measured in the field. To get around this problem, Ciz and Shapiro suggest an approximate equation (Equation 1) by replacing

their heuristic parameter by elastic properties of the pore-filling material.

$$K_{sat} \approx \frac{\eta_0^A \left(\frac{1}{K^B} - \frac{1}{K^A} \right) + \left(\frac{1}{K^B} - \frac{1}{K_{dry}} \right)}{\frac{\eta_0^A}{K_{dry}} \left(\frac{1}{K^B} - \frac{1}{K^A} \right) + \frac{1}{K^B} \left(\frac{1}{K^B} - \frac{1}{K_{dry}} \right)}$$

where

K_{sat}	Effective bulk modulus
η_0	Porosity
K_{dry}	Dry (drained) rock bulk modulus
K^A	Bulk modulus of the pore-filling mineral
K^B	Bulk modulus of the solid matrix

Equation 1. Solid substitution equation

Since Equation 1 is an approximation to the exact solid substitution equation, its accuracy will naturally depend on the rock microstructure. Therefore, to analyze its validity, a numerical simulation system is set up in COMSOL Multiphysics, with both pore-space and rock frame filled with elastic solids. The simulation was first benchmarked on arbitrary synthetic pore geometry (not detailed here) with known exact elastic solution given by Hill [3] for the case when both frame and pore-space solids have the same shear stiffness.

3. Use of COMSOL Multiphysics

The structural mechanics module of COMSOL Multiphysics is used to simulate pore-scale equations of linear elasticity and momentum balance along with continuity boundary conditions. A volumetric strain is applied and the numerically obtained effective bulk modulus is compared with the theoretical predictions.

4. Digital Rocks

A clean Fontainebleau Sandstone sample is scanned with a microCT scanner. 1020 images were obtained, each with 1012x1024 pixels, representing a spatial resolution of 2.3 cubic microns per voxel. Figure 1 shows one of these images. The mineral matrix (higher intensity) and dry pores (lower intensity) is clearly visible.

In a producing reservoir, the void space can be filled with gas, oil, water, bitumen, kerogen, or a combination of all.

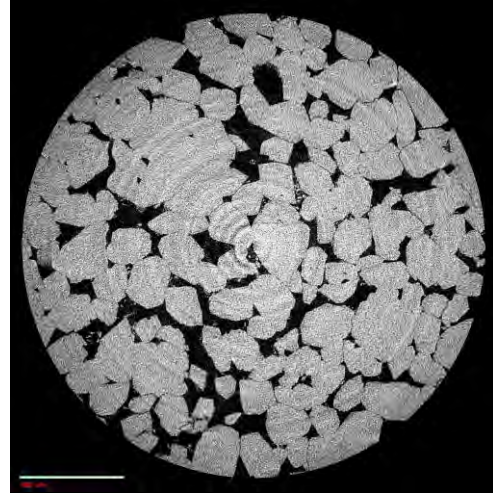


Figure 1. CAT CT Scan Image

The scanned 2D images are stacked and reconstructed into a 3D volume, as shown in Figure 2.

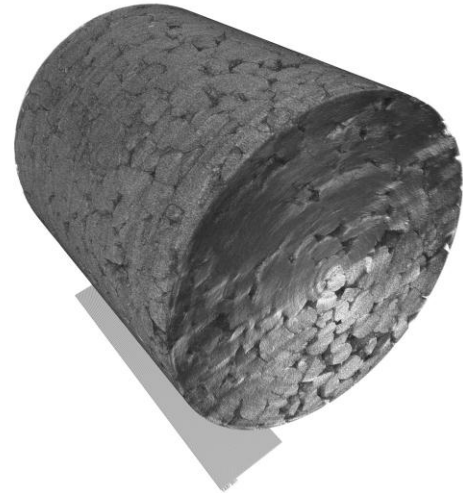


Figure 2. 3D Reconstruction & Rendering of Core Sample Volume

The digital rock volume is then segmented into pores (black) and mineral matrix (blue), as shown in Figure 3.

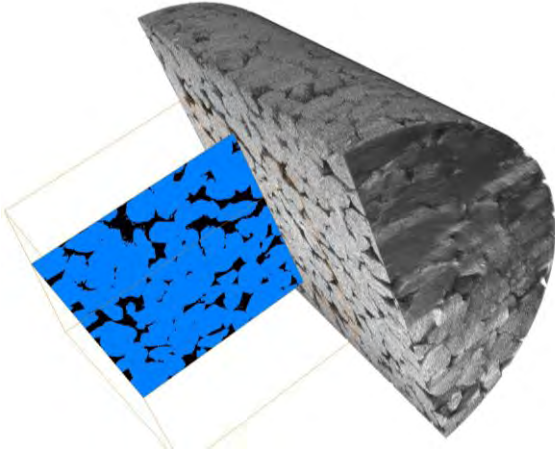


Figure 3. Pore segmentation

Next, a surface of the rock geometry can be reconstructed. Due to the constraints of the computational resources, this project focus on a small rock fragment, with roughly 3-4 grains on each side, as shown in Figure 4. Tetrahedron mesh element is generated and exported to Comsol for multiphysics simulation.

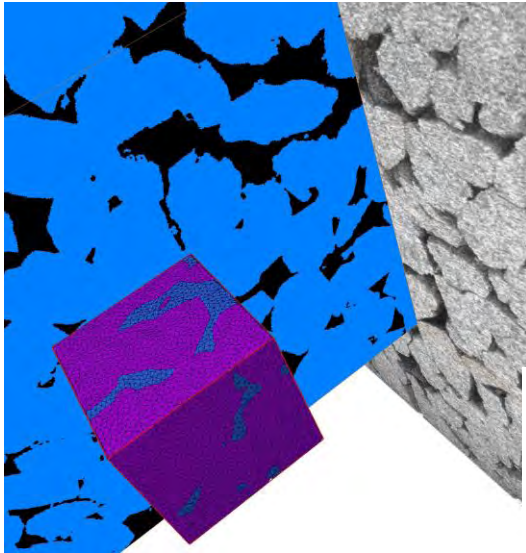


Figure 4. Mesh reconstruction

Additionally, important rock properties can be calculated [7][3] as shown in Table 1.

Porosity prediction is consistent with the physical lab measurement. The results above also indicates that the rock sample is marginally

percolating, which is something remaining to be investigated further with physical lab experiment.

Porosity	0.168
Permeability X	1×10^{-3} Darcy
Permeability Y	0.89×10^{-3} Darcy
Permeability Z	0.57×10^{-3} Darcy

Table 1. Petrophysical parameters of the sample

5. Simulation result and discussion

With the pore network model reconstructed from the digital rock data, a series of simulations are conducted on 9 different K^A parameters, summarized in Table 2 below.

In Figure 5, the numerical values derived from Comsol simulation (grey circles) are plotted against the theoretical model (dashed line, Equation 1). One other exact solid substitution model is also investigated and plotted but the model and detailed results will be discussed elsewhere.

0	0.01×10^{10}
1	0.41×10^{10}
2	0.81×10^{10}
3	1.21×10^{10}
4	1.61×10^{10}
5	2.01×10^{10}
6	2.41×10^{10}
7	2.81×10^{10}
8	3.21×10^{10}

Table 2. Different K_{pore} (Unit: Pa) parameter used for simulation

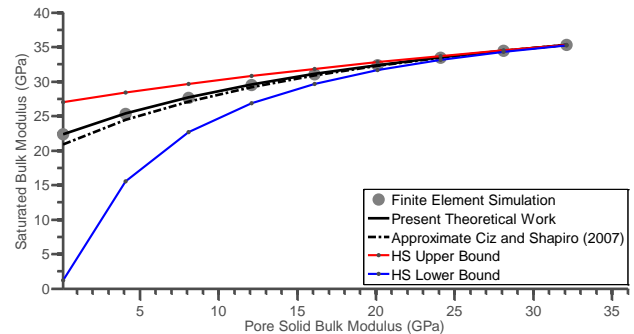


Figure 5. Pore Mineral Shear Modulus : 2 GPa, Volumetric Strain: 10^{-3}

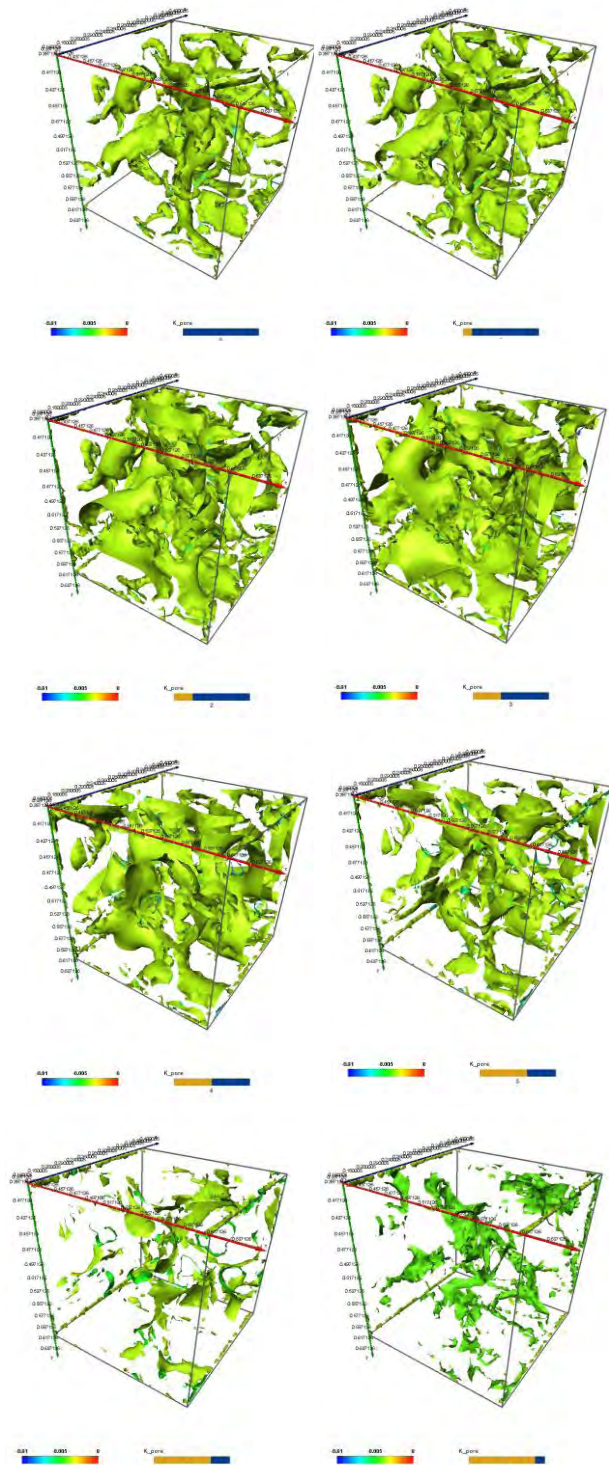


Figure 6. Isosurface of stress at 9×10^7 for eight different K^A parameters, all colored by the strain (color bar)

For a particular shear modulus of the pore-filling material, the approximate Equation 1 works very well for a range of pore-filling material bulk moduli. This confirms the accuracy of the approximate equation for the particular sandstone rock sample used in this study.

Figure 6 shows the isosurface of stress at 9×10^7 for eight different K^A parameters, all colored by the strain (color bar). The last is omitted because there no interesting features left.

6. Conclusions

This paper applied a digital analysis framework to study the accuracy of a theoretical rock model. Benchmarked numerical simulations, using Comsol Multiphysics, are conducted on digital rock geometry, extracted using Avizo software, from 3D imaging scans of a sandstone rock.

The approximate Ciz and Shapiro model for solid filled rocks works well for a clean sandstone rock. This study can be further extended to test the accuracy of the model for different rock types, including fractured sandstones or carbonate rocks. Also, under various conditions, earth materials are known to show different mechanical behaviors including elastic, viscoelastic, plastic, etc. These can be simulated with Comsol Multiphysics on the same microstructure.

It is also noted that the proposed full digital workflow offers great potential in studying rocks at various scales as well as porous material in general.

7. References

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8. Appendix

8.1 From Avizo to Comsol Workflow

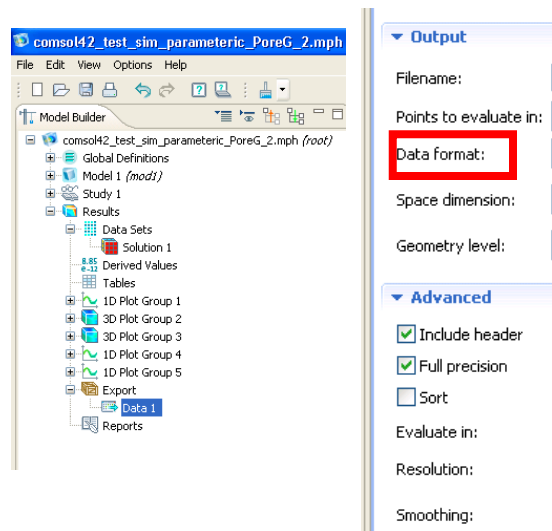
Data to be interfaced: Tetrahedron unstructured mesh generated by Avizo

- Step 1: Use *TetraGen* to generate tetrahedron element data
- Step 2: Use *File/Save Data As* to save the tetrahedron element data into *Nastran* format

8.2 From Comsol to Avizo workflow

Data to be interfaced: Comsol simulation fields along with Tetrahedron unstructured mesh

- Step 1: In Comsol 4.2 interface, select a *Data* under *Export* entry in *Model Builder* tree view.



- Step 2: In *Output* section, make sure the Data format is set to *Sectionwise Data*. This is the only option that will allow the output of the connectivity of the unstructured mesh. Connectivity is a multiple variable array, integer, with each entry of the array listing the IDs of the nodes that are composing the tetrahedron. The IDs are referring to the indices of the array that is listing the coordinates of nodes.
- Step 3: Translating, using a text editor, a Comsol *Sectionwise Data* into *amira mesh *.am* format. See section 8.3.
- Step 4: Load **.am* file(s) using *File/Open Data* or *File/Open Time Series Data* using Avizo GUI.

8.3 Converting Comsol solution data into *.am format

```
HEADER - Comsol
% Model:      comsol42_test_sim_parametric_PoreG_2.mph
% Version:    COMSOL 4.2.0.228
```

```
% Date: Sep 14 2011, 13:36
% Dimension: 3
% Nodes: 58597
% Elements: 273294
% Expressions: 18
% Description: Pressure, Strain
```

HEADER - Avizo

```
# Avizo ASCII 1.0
```

```
define Nodes 58597
define Tetrahedra 273294
```

```
Parameters {
  Info "This is an AvizoMesh example",
  Pi 3.1459
}
```

```
Materials { {
  Name "Stone",
  Color 0.8 0.3 0.1
} {
  Name "Void",
  Color 0.0 0.3 0.8
}
}
```

```
Nodes { float[3] Coordinates } = @1
Tetrahedra { int[4] Nodes } = @4
```

```
Nodes { float P0 } = @8
Nodes { float E0 } = @9
```

```
Tetrahedra { byte Materials } = @12
```

```
Field { float P0 } = Linear(@8)
Field { float E0 } = Linear(@9)
```

NODE COORDINATES - COMSOL

```
% Coordinates
0.48305195569 0.51833164691 0.37172931432
```

NODE COORDINATES - AVIZO

```
# Coordinates
@1 THIS HAS TO MATCH AVIZO HEADER
KEYWORDS "Nodes"
0.48305195569 0.51833164691 0.37172931432
```

CONNECTIVITY - COMSOL

```
% Elements (tetrahedra)
4 3 2 1
```

CONNECTIVITY-AVIZO

```
# Elements (tetrahedra)
@4 THIS HAS TO MATCH AVIZO HEADER
KEYWORDS "Tetrahedra"
4 3 2 1
```

DATAFIELDS-COMSOL

```
% Data (solid.p (Pa) @ K_Pore=1e8)
3.2432993793746352E7
```

DATAFIELDS-AVIZO

```
# Data (solid.p (Pa) @ K_Pore=1e8)
@8 THIS HAS TO MATCH AVIZO HEADER
KEYWORDS "field"
3.2432993793746352E7
```

It is suggested that when Comsol fields is output, each file contains one field with one "*parameter values*" (e.g., time). This is not mandatory but will make the management of multiple time steps (or parameter values) easier by using simply "Load time series".

In terms of text editor, the following software are recommended,

- On Linux, VI or Emacs both work well.
- On Windows, do not use any Microsoft text editors (including Wordpad, Notepad, or MS Word). Instead, use textpad (www.textpad.com), which provides a free evaluation.